AN INVESTIGATION OF STEAM CURING OF CONCRETE AND ITS EFFECT ON COMPRESSIVE STRENGTH

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THE UNIVERSITY OF ALBERTA

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SYNOPSIS

This paper presents the results of an investigation of the effects on the compressive strength of 4" x 8" test cylinders of normal concrete mixes subjected to curing temperatures from 135 degrees F. to 200 degrees F. for 24 hour periods, and subsequent storage periods. Two methods of application of such elevated curing temperatures were used; (a) Concrete in sealed molds immersed in heated water maintained at constant temperatures, and concrete in sealed molds subjected to various steam curing cycles. (b) Bare concrete cylinders subjected to saturated atmospheric pressure steam curing cycles.

Also presented is the design, construction and operation of a steam curing kiln which is equipped with various control mechanisms capable of producing, and reproducing a large number of saturated atmospheric pressure steam curing temperatures and cycles.

The results indicate that while "Thermal Shock" and excessive temperatures have adverse effects on the compressive strength, under properly "controlled conditions" high early strengths result. However, the later age strengths can be expected to be less than those for the corresponding standard moist cure. Also indicated are the facts that; (a) Preset periods from 2 - 6 hours are beneficial. (b) Subsequent moist curing has some slight advantage, especially at the lower temperatures used. (c) Strengths are affected to some extent by the type of curing cycle.

INTRODUCTION

In the modern production of concrete products it is frequently desirable to hasten the curing process. This necessity arises generally for two reasons; firstly to release molds and pallets as quickly as possible, and secondly to put the finished article on the market as soon as possible, and so avoid having to provide continuous storage space. Although some acceleration of setting and hardening can be achieved by chemical means, steam curing is more effective and more susceptible to accurate control.

There are many references in published literature to experiments in steam curing, but the results are in some respects contradictory, and are not easily applied to commercial practice.

The main processes in general use may be conveniently divided into three classes: high pressure, low pressure continuous, and low pressure intermittent.

The high pressure process requires an especially constructed steel chamber or autoclave and since the chamber is steam tight a continuous program is not possible. Control is achieved by regulation of either pressure or temperature alone since excess water is kept in the chamber. Pressures up to 200 pounds per sq. in. and temperatures of 195 degrees C. are obtained and the steaming period is comparatively short. For the high pressure process, the following results are obtainable:[1]

---

1 Taken from a progress report by the ACI Committee 716. April 1944 pp 409-16 (V 40)

1. A rapid increase in strength results due to the higher temperatures; and the units are suitable for use within 24 hours after molding, and the high early strength is permanent.
2. With certain aggregates a lime-silica reaction may take place between the cement and aggregates, and strengths in excess of that predictible from the effect of increased hydration may be developed.
3. Reduction in initial drying shrinkage and the reversible wetting and drying movements occur.
4. An increased resistance to sulphate attack is obtained.
5. The product is in a substantially drier condition and lighter in color than moist cured concrete.
6. Lower bond stress between steel and concrete is obtained.

Factors such as size and shapes of units, aggregates, and methods of racking, consistency of mix, age of molded units before being exposed to steam pressure, time required to raise steam pressure and temperature to maximum from atmospheric, and time required to release temperature and pressures to atmospheric, may have considerable influence in determining the proper economic pressure, temperature and cycle of steaming. Various cycles have been outlined in published articles.[2]

---

[2] Studies of High Pressure Steam Curing by J.C. Pearson and E.M. Brickett. A.C.I. Proceedings, Vol. 111, 1932, pp 537.

The Effect of High Pressure Steam on Crushing Strength of Portland Cement Mortars and Concretes by R.J. Wig. A.S.T.M.

Owing to the high capital cost of equipment, high pressure steam curing is recommended only where it is important to reduce shrinkage or to increase sulphate resistance, or where the early maximum strength is desired.

Low pressure continuous steam curing is best suited to mass production. There are generally two methods used, and temperatures are limited to 100 - 200 degrees F.

In a short high temperature kiln, the units are loaded on trucks. The kiln is fitted with doors, and the haulage is intermittent, usually one truck advancing into the kiln, and one truck moving out at the same time.

A long tunnel type kiln may be designed to have a temperature gradient formed at each end. During the steaming operation doors are left open, and haulage is usually continuous, the rate depending on the time-length of steaming allowed.

The spacing of the units may or may not be important, and depends on the method of heating.

The low pressure intermittent process is carried out in batteries of curing chambers, at temperatures also below 200 degrees F. The batteries are sometimes designed to take a day's output and steaming commences at the end of the day. The steam is usually cut off during the night so that kilns may be drawn at the beginning of the next day. Here agin, spacing of units may or may not be important.

In the United States and Canada the Low Pressure Intermittent process is favoured, and several different cycles of steaming are used. The one most favored is as follows:

Immediately after being molded, the units are placed in the kiln and when the kiln is filled the doors are closed. A waiting period of 2 - 6 hours permits a partial set of the concrete. The steam is then turned on and the temperature raised to a maximum value, predetermined by tests to give best results. (The rate of temperature rise usually is limited to a maximum of 1 degree F. per minute.) When the Maximum temperature has been reached the steam is cut off and the kiln is allowed to cool down. This period is called a "soaking period", and is maintained as long as possible. It is followed by a further period of drying to remove moisture from the unit, so that it will pass the A.S.T.M. Moisture Specification of less than 40 percent of the total absorption. The kiln is then unloaded and is ready for another run.

At least two companies in the United States have developed kilns with good automatic control devices to make each steaming cycle easily reproducible.[3]

3
"Curing - Most Efficient Methods Determined by Tests" by George A. Mansfield. "Rock Products" Journal February 1947.

"Curing - A Problem in Thermodynamics" by George A. Mansfield "Rock Products" Journal August 1948.

"High-Temperature. High-Humidity" by Bior Nordberg. "Rock Products" Journal January 1947.

PART I

THERMODYNAMIC AND OTHER CONSIDERATIONS PERTINENT TO OBTAINING A PROPER CURING ATMOSPHERE FOR AN ACCELERATED CURING PROCESS WITH STEAM

Concrete when properly cured at normal atmospheric temperatures results in a tough building material, but so often concrete masonry cured at high temperatures is brittle and subject to breakage during handling, though still satisfactory when considered in the light of strength and moisture specifications as designated by A.S.T.M. This brittleness can be attributed to the fact that the binding material, Portland Cement, has been damaged during the curing process. Where the product has been cured by high temperatures it can be concluded that there was not a sufficient quantity of moisture in immediate contact with the cement mortar, and hence the normal products of hydration were not able to develop.

From thermodynamics, it is indicated that equilibrium temperatures below 212 degrees F. are impossible at atmospheric pressure without having a mixture of steam, water, and air.

In terms of Phase Language, the variance of a system is given by: $V = C + 2 - P$

where,

V is the variance or degrees of freedom

C is the number of components

P is the number of phases

For a system of steam and water C is equal to 1 and P is equal to 2, and thus V equals 1, which means the system has but one degree of

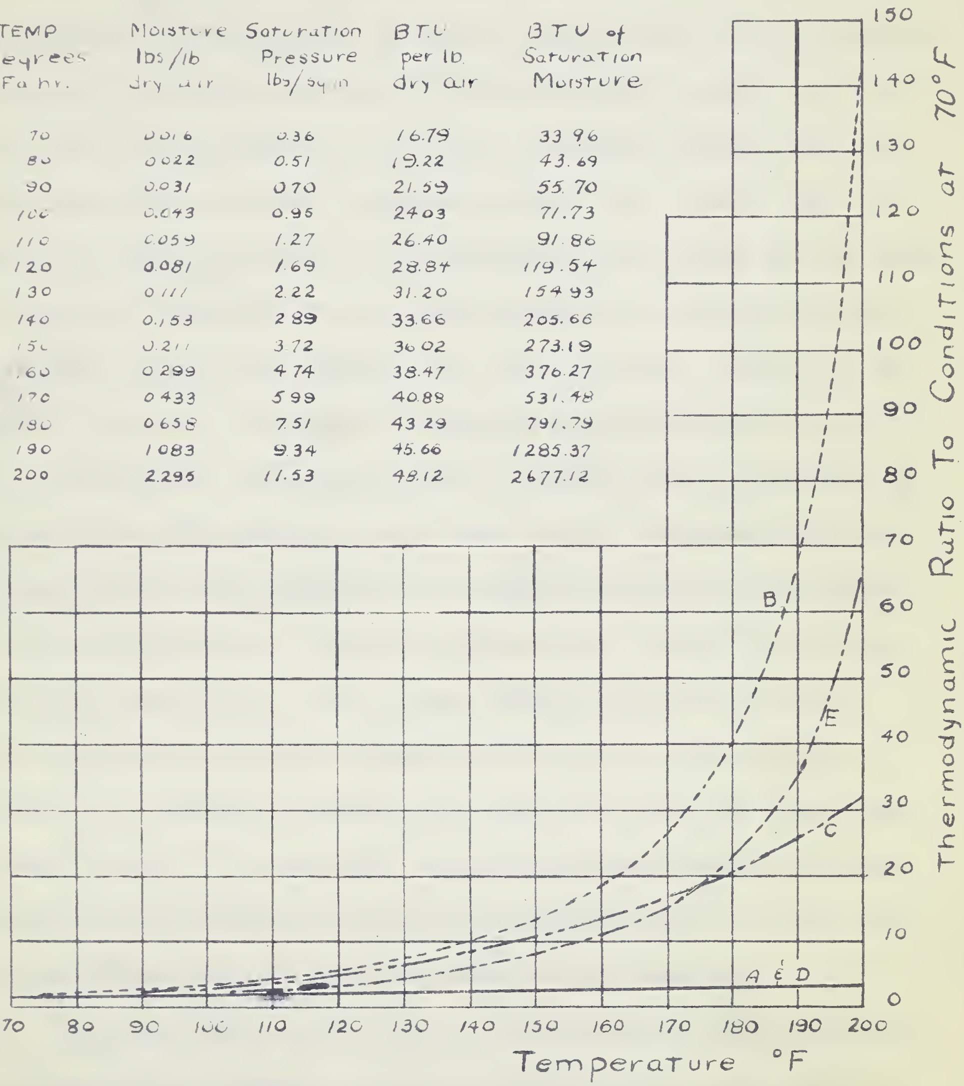
freedom. Thus for atmospheric pressure there is a unique temperature for a condition of saturation, viz; 212 degrees F. at normal atmospheric pressure.

Now if air is also added to the system, the C is equal to 2, P is equal to 2, and V equals 2, indicating two degrees of freedom, viz. we may arbitrarily fix the pressure and temperature, and obtain a condition of saturation.

A study of air at various temperatures, will indicate the difficulties in maintaining a moisture condition in contact with cement during a curing cycle. Thermodynamics show that the higher the dry bulb temperature, the greater will be the grains of moisture or pounds of water per pound of air required to maintain a condition of 100 per-cent relative humidity. The data given in figure I, are taken from the table of "Thermodynamic Properties of Moist Air" contained in the American Society of Heating and Ventilating Engineer's Guide, 1946, and indicate the amount of moisture necessary to maintain 100 percent relative humidity. From this it is seen that for a system having a dry bulb temperature of 130 degrees F., (that is to say, 100 percent relative humidity) 0.081 pounds of moisture per pound of dry air is required. If the dry bulb temperature is increased to 180 degrees F. without an increase in pounds of moisture per pound of dry air, the wet temperature will be 132.5 degrees F. with a resultant humidity of 29.5 percent. This physical phenomenon clearly indicates the need for a greatly increased moisture content at higher temperatures. The amount of moisture required is 2.295 pounds per pound of dry air for 100 percent

THERMODYNAMIC PROPERTIES of MOIST AIR

TEMP Degrees Fahr.	Moisture lbs/lb dry air	Saturation Pressure lbs/sq in	B.T.U. per lb. dry air	B.T.U. of Saturation Moisture
70	0.016	0.36	16.79	33.96
80	0.022	0.51	19.22	43.69
90	0.031	0.70	21.59	55.70
100	0.043	0.95	24.03	71.73
110	0.059	1.27	26.40	91.86
120	0.081	1.69	28.84	119.54
130	0.111	2.22	31.20	154.93
140	0.153	2.89	33.66	205.66
150	0.211	3.72	36.02	273.19
160	0.299	4.74	38.47	376.27
170	0.433	5.99	40.88	531.48
180	0.658	7.51	43.29	791.79
190	1.083	9.34	45.66	1285.37
200	2.295	11.53	48.12	2677.12



—— Curve A - represents temperature ratios

----- Curve B - moisture requirements for dry air saturated

—·-·— Curve C - shows progressively increasing saturation pressures

—— Curve D - indicates heat content of dry air

—·-·— Curve E - heat content of moisture in dry air saturated

Fig 1

relative humidity at 200 degrees F., and 0.658 pounds per pound of dry air for 180 degrees F.

There is some doubt that 100 percent humidity is necessary for proper curing from a moisture standpoint. However, when we consider the vapor pressures of the moisture at various temperatures, it is seen that 130 degrees F. the vapor pressure of the water vapor is 2.22 pounds per square inch; for 180 degrees F. it is 7.51 pounds per square inch, and at 200 degrees F. it is 11.53 pounds per square inch. Since there is initially at least, free water in the concrete units, there will be equal vapor pressures, provided that the kiln atmosphere is fully saturated. However when the kiln atmosphere is not fully saturated, there will be developed a pressure differential tending to move the water from the unit to the surface. For example, if a 50 percent relative humidity is existing in the kiln atmosphere with both the kiln atmosphere and block at a temperature of 180 degrees F., the vapor pressures in the concrete unit and the kiln are 7.51 pounds per square inch, and 3.75 pounds per square inch respectively. For the same temperatures and 90 percent relative humidity in the kiln atmosphere, the vapor pressures are respectively 7.51 pounds per square inch, and 6.75 pounds per square inch. From these figures it is seen that unless 100 percent relative humidity is maintained, the moisture required for hydration will be removed from the concrete mass and so injure the quality of the concrete.

In fact even with 100 percent relative humidity the adiabatic heat produced by the chemical reactions of hydration is sufficient to raise the temperatures inside the block, so that a pressure differential will exist, and over a period of time cause a removal of water from the concrete mass.

The pressure differentials produced by the partial vapour pressures will be evident between kiln atmosphere and the outside air, and thus will also tend to cause moisture to move from the inside of the kiln to the outside. This necessitates extreme care in kiln construction. For example, if the kiln is operating at 170 degrees F., the partial pressure of the saturated vapour is 12.203 pounds per square inch. If at the same time the air outside the kiln is saturated at 70 degrees F. the vapour pressure is 0.739 pounds per square inch. If the outside air were at 50 percent relative humidity, then the pressure differential is further increased. Kilns operating at higher temperatures would still further increase the pressure difference.

A graphical picture of the relative amount of moisture, amount of heat required, and saturation pressure, is provided by the curves in figure 1, page 7. These curves are taken from reference number 3, and are established by plotting each thermodynamic property from 70 degrees to 200 degrees F. in 10 degree increments, and expressed as a percentage ratio to the condition at 70 degrees F. Curve "A" represents the temperature ratios and is, naturally, a straight line. Curve "B" expresses the moisture requirements for saturated dry air, and forcibly illustrates the progressively increasing demand for moisture to maintain total saturation as the temperature is increased. Curve "C" portrays the progressively increasing saturation pressures, and although it is not as pronounced as Curve "B" it distinctly shows the difficulty of holding the atmosphere at a proper curing condition in the kiln. Also included in figure 1 is the B.T.U. requirement to heat dry air.

Curve "D" is identical to temperature increase Curve "A". Curve "E" shows the B.T.U. requirement ratio to heat totally saturated air, and indicates the accelerated heat requirement necessary for increasing the temperature of a saturated atmosphere.

Carbonation of the concrete is also an important factor that must be considered in the curing of concrete masonry. By carbonation is meant the absorption of carbon-dioxide from the kiln atmosphere when there is not sufficient moisture present during the curing process. Carbonation can be beneficial or detrimental depending on when it occurs. If it occurs before the period in which the Portland Cement hydration compounds are being formed, it is detrimental. However, if it occurs after the hydration it is beneficial.

The detrimental effect of carbonation is the tendency to produce a brittle product, although strengths may be favourable. In view of this harmful effect of carbonation during hydration, caution must be observed in the selection of curing methods, particularly with a system using the products of combustion as part of the kiln atmosphere. In the process of fuel combustion free oxygen of the air combines with fuel carbon to form carbon-dioxide, as well as some carbon-monoxide. When these products of fuel combustion become part of a kiln atmosphere, and the atmosphere is not changed, high concentrations of carbon-dioxide and carbon-monoxide can occur, with harmful effects on the concrete products, as well as possible detriment to the efficiency and health of the employees of a concrete products plant. Care must also be exercised in limiting the amount of carbonation, even after hydration, due to the

subsequent shrinking caused by formation of calcium carbonate. This shrinking can cause fine cracks in shells and webs, if the surface drying is more rapid than that of the interior.

The fact that a vapour pressure differential within the interior of concrete units exists when the kiln atmosphere is not saturated, or at a lower temperature, can be utilized to remove excess moisture from the product at the end of the curing process by deliberately creating the necessary atmosphere. Care must be exercised in doing so, to be sure that "thermal shock" and excess stresses capable of producing hair cracks are not produced. Also when temperatures in excess of 105 degrees C. or 221 degrees F. are maintained, the chemically compounded water is driven from the hydrated cement, which tends to destroy the cement gel. Therefore temperatures in excess of 200 degrees F. are not advisable for atmospheric pressure curing or drying of the concrete products.

From the principles outlined in the former pages it is possible to design two tentative curing cycles of 24 hours' duration and having the following characteristics:

1. A gradual and constant time-temperature gradient maintained over a period of 9 hours to reach the maximum temperature required. The same time-temperature gradient maintained from the maximum temperature to room temperature. The 6 hours immediately after mixing is used for an "initial set" period.

2. A 6 hour "initial set" period is provided immediately after mixing, followed by a rapid heating-up period to a temperature 20

degrees F. below the maximum temperature. This is then followed by a gradual rise in temperature over as long a time as possible to reach the maximum temperature required, followed by as rapid a cooling down period as possible. (The gradual temperature rise portion of the cycle is designed to keep temperatures in concrete units equal to or less than kiln atmosphere temperatures at all times.)

These two tentative cycles plus a third cycle, consisting of a 6 hour waiting or initial set period, followed by a rapid heating up period to the maximum temperature, and at the end a rapid cooling down temperature, to complete the 24 hour time limit, will be used in this investigation. Each cycle will operate at three different temperatures of 135 degrees F., 160 degrees F. and 185 degrees F. respectively, giving 9 different cycles of curing conditions.

PART II

LABORATORY EQUIPMENT

CHAPTER I

STEAM CURING CABINET

INTRODUCTION

The conditions of heat transfer to concrete units in steam curing chambers or kilns are complicated. Heat may be transferred by radiation from walls, ceiling and roof, by convection of heated air and steam, and by condensation of steam on the surface of concrete and molds. The heat thus transferred heats the interior of the units by conduction.

The heat supplied to the chambers, and the heat generated by the chemical action of hydration is expended, in heating the concrete to the desired temperature, as heat losses to the atmosphere from the chambers, as well as heat removed in the concrete when taken from the chamber. Heat losses to the atmosphere from the chamber may be reduced by the use of thermal insulation of walls, roof and floors. The latent heat in the units can be utilized by cutting off the heat some time before the chamber is to be discharged.

The method of heating affects the distribution of temperature throughout the kiln. In one form of kiln the walls are heated by steam pipes, and only sufficient live steam and water are injected into the chamber to maintain a saturated atmosphere. In this type the spacing of units is quite critical.

In others, heating is produced by injection of steam, water and air. The principle method of heating is by condensation, and

uniform temperatures can be more easily maintained because condensation takes place more rapidly on the cooler units. The water is added usually in the form of fog spray to ensure saturated conditions and the air is added to ensure adequate mixing and movement of atmosphere as well as to obtain a stable saturated atmosphere.

In the design of the steam curing cabinet used in this investigation, the latter method of heating is used, since it is the most practical and lends itself to accurate control.

<u>Procedure and Design and Construction of a Steam Curing Cabinet</u>

The tentative requirements of a steam cabinet suitable for the aims of this program are as follows:

1. To maintain a saturated or very near saturated condition of atmosphere at temperatures from 100 degrees F. to 200 degrees F.
2. To provide a means of weighing at least one specimen during a curing cycle, so as to aid in ascertaining some indication as to type of atmosphere being produced.
3. To maintain a required temperature with as small a temperature differential as possible over considerable lengths of time, as well as being capable of wide ranges of temperature change with time. In addition to give a large number of possible procedures and to be capable of closely reproducing such procedures at will.
4. To be as simple and economical in operation as possible.

In part I page 5 it was indicated that it is impossible to

obtain equilibrium temperatures of from 100 - 200 degrees F. with complete saturation, at atmospheric pressures, without having a system of steam, water and air.

Therefore, it was decided to introduce steam, water and air first into a mixing chamber before they entered the kiln. Further, water would also be added directly to the atmosphere inside the kiln. The air and water would be supplied at a constant rate, and the steam varied, by a thermostatic regulator valve, as required to maintain temperatures. The atmosphere produced in the mixing chamber, or valve, would be introduced at one end of the kiln at mid-height, distributed by a baffle screen, to give an even flow across the curing chamber and passed through a second baffle, before being discharged through a pipe at the opposite end. The condensed or excess water would be removed by a floor drain, connected to the discharge pipe, outside the kiln.

From a consideration of loading and unloading, a rectangular cabinet 5 feet long, $2\frac{1}{2}$ feet wide and $3\frac{1}{2}$ feet high, was decided upon as being the smallest practical size that could be used. This would give a maximum capacity of 20 - 4" x 8" standard concrete test cylinders, or 12 - 6" x 12" standard concrete test cylinders when divided into a top and bottom compartment by an open type shelf, and was considered adequate for this investigation.

Wherever possible use was to be made of standard building materials and plumbing fixtures such as pipe, valves, tubing, etc.

It was decided to use as a steam supply the steam radiator heating system, using exhaust steam from the University of Alberta

power plant supplied at 3 - 4 pounds per square inch and a quality of 0.95, since it was the most readily available.

A "Powers" type "T" direct acting air operated, thermo regulator, and ½" valve capable of delivering 88 pounds of steam per hour at a pressure of 4 pounds per square inch, was selected as the smallest size of valve that could practically be used.

Due to a shortage of space, the cabinet was placed in one corner of the Testing Laboratory in the Civil Engineering Building, as close as possible to a radiator steam supply line. This necessitated pipe lines of ¼" diameter pipe to bring air and water to the cabinet, and in addition made a 140 foot 1½" discharge pipe from the cabinet to a waste water sump necessary, as it was not possible to exhaust to atmosphere, either inside or outside of the building.

Consequently a rectangular cabinet 5' x 2' x 3'-6" with a one brick thick side wall, and 2" thick concrete floor and roof slabs, reinforced with chicken wire, was built on a wooden base 6' x 3', of 2" x 10" planks. The interior was divided into a top and bottom section by an open shelf of 2" x 4" slats supported on aluminum 1¼ x 1¼" angle frame. Access was provided by a 28" x 28" square door, in the side, with refrigerator type seals. The inside surface of brick walls was coated with an asphaltic type kiln liner compound, kindly supplied by the Edmonton Concrete Block Company, Edmonton, Alberta, to make a tight vapour seal.[4]

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[4] The kiln liner is sold by A.C. Horn - 821 Queen St., E., Toronto 8, under the trade name "Horn Kiln Liner".

STEAM KILN
FRONT VIEW

Scale 1" = 1'

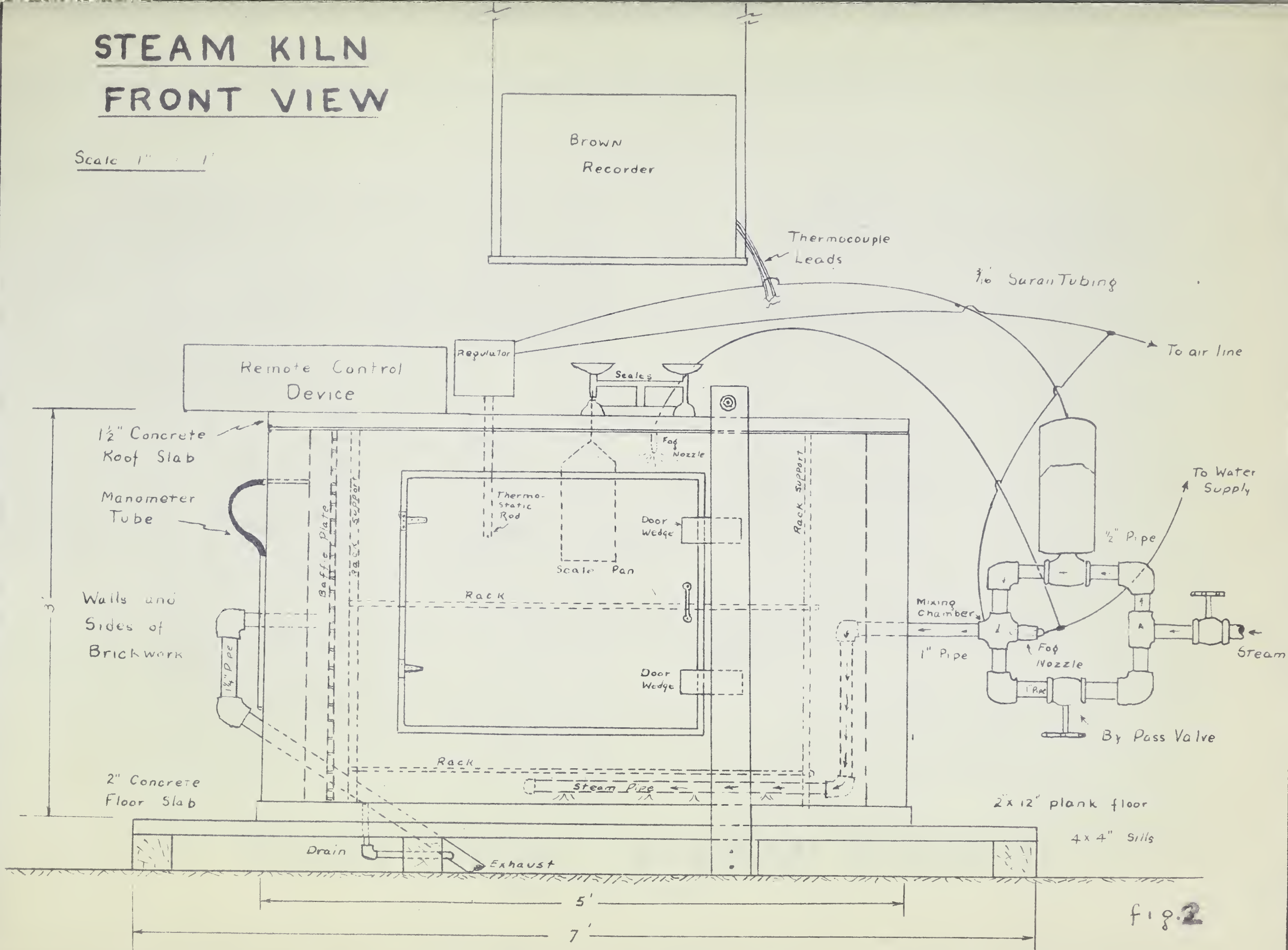
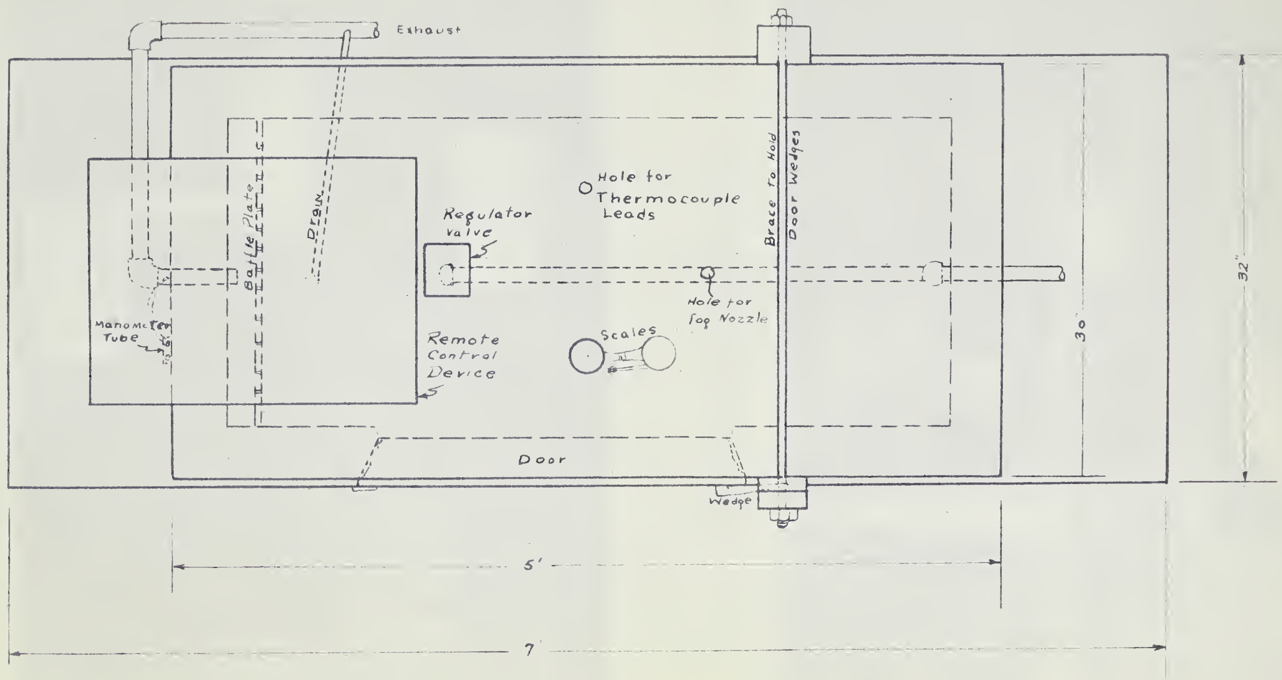


fig. 2



PLAN VIEW STEAM KILN

Scale 1 inch = 1 foot

Fig 3

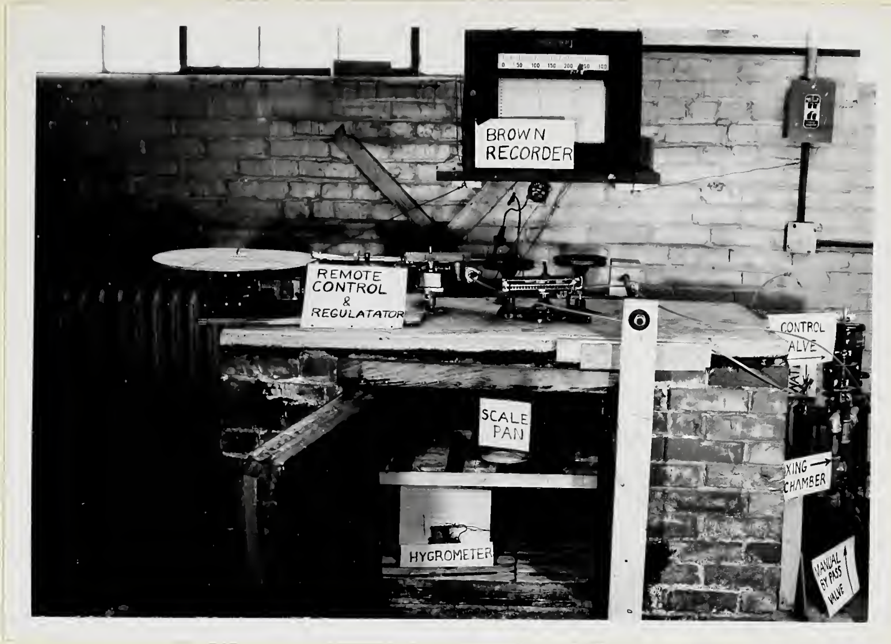


Photo A - Front View of Steam Kiln

Photo B - Steam Inlet - End View of Steam Kiln

Photo C - Outlet End View of Steam Kiln

Photo D - Top View of Steam Kiln

Photo AA - Interior View from Loading Door
of Steam Kiln

Two baffle screens of $\frac{1}{4}$" thick transit board, with 150 - $\frac{1}{2}$" diameter holes, were placed 8" from either end of the kiln. The discharge or outlet pipe was $1\frac{1}{2}$" diameter, placed at mid-height in center of the end of the kiln, and a $\frac{1}{4}$" diameter pipe drain for condensed water placed in the floor, below the transit board baffle screen, and connected by a rubber hose to the discharge line outside of the cabinet. Also placed at the discharge end of kiln was a "U" type water-filled manometer, with the pressure tube leading inside the end wall to measure total pressures inside the cabinet. At the other end of the cabinet a 1" diameter entrance pipe was placed at mid-height leading from the mixing valve or chamber, which consisted of a 1" diameter standard 4-way pipe fitting. Into this fitting was led a $\frac{1}{2}$" diameter pipe from the regulator valve, a 1" diameter pipe from a manual by-pass valve connected to main steam supply, a fog nozzle of type used in air conditioning systems and rated at 0.65 gallons per hour at a pressure of 40 pounds per square inch, connected to the domestic water supply, and an air inlet connected to the air supply line delivering air at 25 pounds per square inch. (See photo B.) On the top of the cabinet was placed the thermo regulator of the "Powers" regulating valve with the thermostatic temperature rod extending into the cabinet through a hole provided. In addition one fog nozzle was extended through the roof slab, so that it would introduce water spray directly to the atmosphere inside the kiln. "Saran" tubing of 3/16" diameter was used to connect water and air supply to the mixing valve, fog nozzles and thermo regulating unit respectively, with brass screw valves placed in the lines so that regulation of each could be obtained as desired. Also placed on the top of the cabinet was a small

beam type balance, with a scale pan suspended on a wire extending through the roof by a small hole provided, so that variations in the weight of a specimen during curing operations could be obtained. Temperature records were provided for by thermocouples placed at strategic points inside the kiln, the lead wires extending through a hole provided in the roof slab to a "Brown" Strip Chart Temperature Recorder unit suspended over the cabinet. (See photo A, C and D).

At this stage of construction, the kiln was operated to test the variation of temperatures within the curing chamber as well as the quality of atmosphere produced and pressures obtained, during operation. The relative humidity of the atmosphere was measured by a thermocouple hygrometer, of the wet and dry bulb type, which consisted of a glass beaker for a water reservoir, into which a flannel wick surrounding the wet bulb thermocouple extended, the dry bulb thermocouple was placed one half inch immediately above the wet bulb thermocouple.

The temperature variation of 20 - 25 degrees F. was found to be far from satisfactory. The resulting wet and dry temperatures indicated that a high relative humidity could be maintained quite easily at all temperatures when steam, air and water were introduced into the kiln. In the absence of air, and/or water, variations of wet and dry bulb temperatures indicated that high relative humidity was not obtained. The water manometer indicated that pressures during operation, even with full steam supply pressures did not increase by more than $1\frac{1}{2}$ inches of water, and for all practical purposes could be assumed equal to atmospheric pressure (viz: $1\frac{1}{2}$" water represents an increase of 0.055 pounds per square inch.)

SCHEMATIC DIAGRAM OF REMOTE CONTROL DEVICE
STEAM C... KILN —

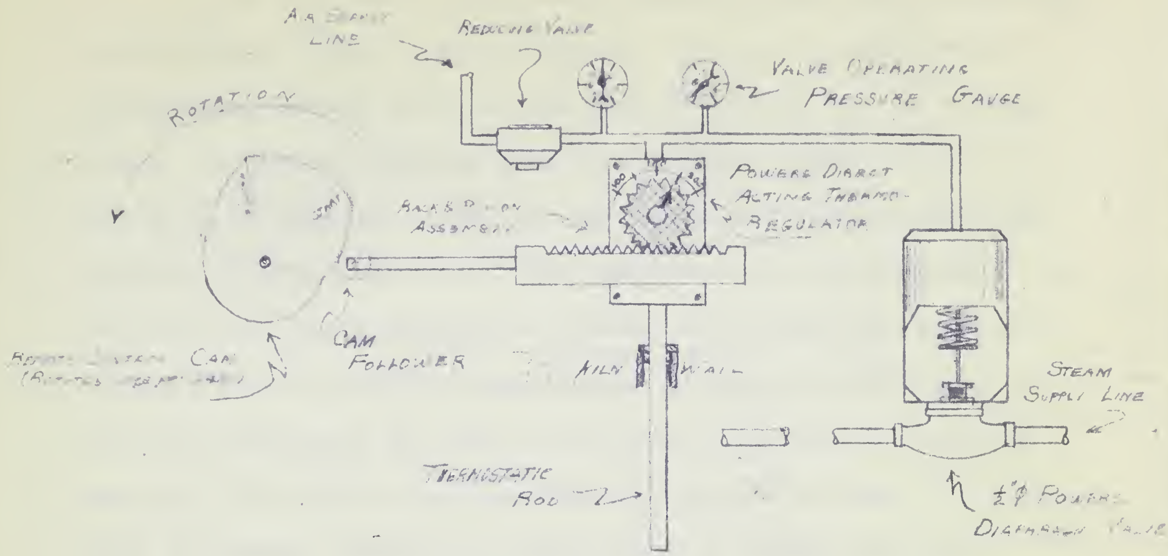


FIGURE 4 (a)

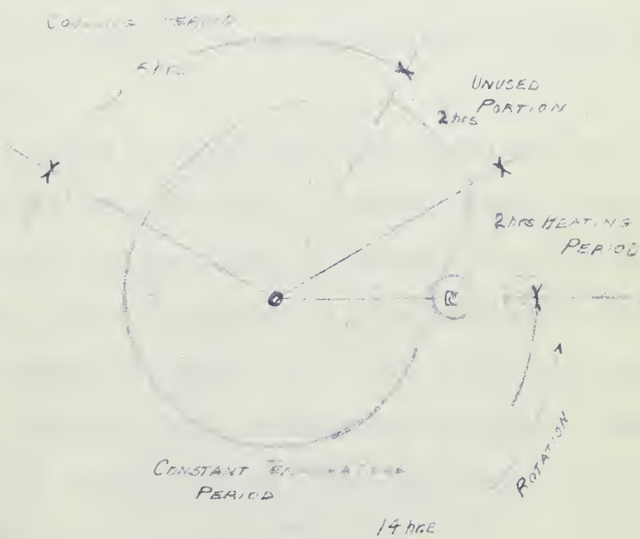


FIGURE 4 (b)

The variation in temperatures inside the kiln was believed due to insufficient mixing of the atmosphere. In order to obtain better mixing it was decided to use a steam manifold leading from the mixing chamber and running along the floor of the cabinet. Small holes were drilled in the manifold so that the curing mixture would be discharged downwards at a 45 degree angle. The small holes give considerable velocity to the curing atmosphere entering the kiln and thus produce a rolling action and provide better mixing. A slat type platform or floor was constructed $1\frac{1}{2}$" above the manifold, to support the concrete specimens. The manifold was made from 1" pipe with two rows of 7 holes, 3/32" in diameter, spaced at 7 inches center to center, the rows of holes were at an angle of 90 degrees from each other. With this method of injecting atmosphere it was found that much better control was available at all temperatures. The temperature differential in any case was not more than 7 degrees F. Thermocouples placed at the floor level, indicated that there was no appreciable increase in temperature caused by the jetting action of the curing atmosphere through the manifold nozzle holes.

In order to fulfill the requirement outlined in Section 2 it was decided that some system of remote control mechanism, would be most economical and practical. A schematic sketch of the principle of such a remote control mechanism is given in figure 4, and the actual mechanism details are shown in photo D. A specially shaped cam, which operates a rack and pinion, rotates once per cycle. (Once per 24 hours.) The pinion is connected to the temperature control valve as indicated in figure 4(b).

The cam is so designed as to give a predetermined cycle of temperatures; a heating up period, constant temperature period, and cooling down period. The cam drive shaft is geared so that it will rotate 330 degrees per 24 hours, and a movement of 3.75 inches of the cam follower is required to obtain the complete range of temperatures from 100 degrees F. to 200 degrees F. In order to obtain a resulting incline on the cam of less than 45 degrees, when operating at a maximum time-temperature gradient of 1 degree F. per minute, a diameter of 20 inches is required for the high lobe portion of the cam. Adjustments of the actual movement of the regulator valve are made on the cam follower push rod. This system allows for an accurate reproduction of any cycle. It also permits a wide range of temperature control because it is merely necessary to substitute a different cam for a different cycle of operation. The principle is simple and relatively foolproof and allows for a complete cycle, without need of control by the operator.

METHOD OF OPERATION AND USE

To put the kiln into operation the procedure is as follows:

1. The kiln is loaded with specimens, spaced within in such a manner that there are equal distances between them. One specimen 4" x 8" cylinder or equivalent size may be placed on the suspended scale pan, when variations in weight with changing moisture conditions in the kiln are required.
2. The wet and dry bulb hygrometer is checked for sufficient water in the reservoir, and the relative positions of the thermocouples, and then placed as close to the middle of the kiln volume as possible.

3. If a record of specimen temperature is desired the termocouple leads connected to thermocouples placed within the specimens are run through the hole provided in the roof, and connected to the "Brown" temperature recorder, and the Recorder put into operation. (The procedure of operation of the "Brown" Temperature Recorder is completely and fully outlined in the "Manual of Maintenance and Operation" supplied with the instrument.)
4. The air and water supply valves are turned on and the fog nozzles checked to see that they are operating properly. (Due to chemicals in the domestic water supply the fog nozzles must be cleaned regularly for proper operation.)
5. When the remote control mechanism is desired, the wooden cam shaped to the required cycle is placed in position and rotated until the mark "Start" is opposite the cam follower, and the spindle plate nut tightened sufficiently so that the cam will not slip when being rotated by the drive shaft. The cam drive motor is started, after ensuring that it is properly lubricated.
6. The kiln door is closed tightly, and the main steam valve is turned on. (For the remote control cycle the manual by-pass valve must always be closed.)
7. When a specimen is placed on the suspended scale pan, the scale is balanced in such a manner that a range of plus or minus 150 grams may be obtained, and so that periodic readings of the weight during the cycle of operation may be taken.

For a record of kiln atmosphere temperatures, 8 thermocouples placed at the eight corners of the kiln volume are connected in a "parallel hook-up", to the number one junction point of the "Brown temperature recorder. This gives an arithmetical average of the eight temperatures indicated by the thermocouples. The wet and dry bulb temperatures of the hygrometer are recorded by the numbers 2 and 3 junction points of the "Brown" temperature recorder respectively.

When a cam for a new design curing cycle is desired for the remote control mechanism, it can be manufactured by the following procedure:

On a suitable piece of ¼" thick plywood enscribe a 20" diameter circle, and mark off an angle of 30 degrees. The arc subtended by this angle is the unused portion of the cam, since the cam drive shaft turns a total of 330 degrees per 24 hours. The arc subtended by the 330 degree angle is then divided into 24 segments, and numbered in a clockwise direction. Each of these segments represent one hour of time. The positions or times at which changes in the time-temperature gradients are required for the designed cycle, can then be marked on the circumference of the circle. The distance that the cam follower moves must be obtained by actual measurements when the kiln is operating at the specified temperatures. These distances are then plotted on the radial lines at their corresponding time-points on the cam. The curves joining the points are then plotted using principles of geometry. (For constant time-temperature gradients, the curve is a logarithematic spiral that can be approximated closely enough by arcs of a circle, provided the time elapsed from point to point is not greater than 4 or 5 hours. Where time elapsed is longer, 2 or more centres must be obtained

to approximate the logarithmatic spiral curve by use of arcs of circles.) The cam can then be cut and sanded to the desired curves, a $\frac{1}{4}$" diameter hole drilled in the centre and the cam put into operation.

Conclusions

The results of the investigation indicated that the steam curing atmosphere created was suitable for properly curing concrete, as evidenced by a comparison of the results from bare cured cylinders and cylinders cured in sealed molds. In all cases the bare cylinders directly exposed to the kiln atmosphere obtained strengths equal to or greater than the strengths obtained by the sealed molds. (See results of cylinders D9, D10, D11 and D12 of each mix.)

Other evidence of the production of a proper curing atmosphere is provided by the results of record of changes of weights of cylinders suspended on the scale pan during curing treatment. Such records were taken at random during the investigation and results are given for three mixes.

Mix No. 1D - Type I Curing Cycle - 135 degrees F. mix temperature

Date	Time	Change in Weight (gns)	
Jan. 15	3.00 p.m.	0.0	start of cycle
	3.30	+9.5	
	3.45	+13.5	
	4.10	+10.5	
	4.30	+ 8.3	
	5.30	+ 8.3	
Jan. 16	8.00 a.m.	+13.5	
	8.40	+13.5	
	9.15	+ 8.3	

<u>Mix No. 1D</u> - Cont'd

Date	Time	Change in weight (gns)	
Jan. 16	9.30 a.m.	+ 7.2	
	11.00	+ 2.0	
	11.45	- 5.0	end of cycle

<u>Mix No. 5D - Type I Curing Cycle - 180 degrees F. mix temperature</u>

Date	Time	Change in weight (gns)	
Jan 22	3.30 p.m.	0.0	start of cycle
	5.45	+11.0	
Jan. 23	9.30 a.m.	+18.0	
	11.30	+18.0	end of cycle

<u>Mix No. 7D - Type II Curing Cycle - 185 degrees F. mix temperature</u>

Date	Time	Change in weight (gns)	
Jan. 25	3.20 p.m.	0.0	start of cycle
	3.35	+11.0	
	9.15 p.m.	+18.0	
Jan. 26	8.05 a.m.	+18.0	
	10.00	+18.0	
	11.25	+19.0	end of cycle

The remote control mechanism worked quite satisfactorily in all cases. Inherently the mechanical remote control required adjustments for each change of temperature range, and where such steam cycles would be employed in commercial kilns, an electronic control would be much more satisfactory.

The results of this investigation indicated that a proper curing condition could be maintained by the kiln for any desired temperature between 100 degrees F. and 200 degrees F.

CHAPTER II

ANCILLARY EQUIPMENT

Laboratory Concrete Mixer

Two types of concrete mixers were used in this investigation:

- A $1\frac{1}{2}$" cubic foot "Lancaster" Mixer, type - SKG Serial No. 303, manufactured by Volta Manufacturing Company, Limited, Welland, Ontario. (See photo E.) This mixer is designed for laboratory work, and has an open circular removable type drum in which the concrete is mixed. Vertical mixing blades rotate in an opposite direction to the drum and can be raised vertically to allow removal of the drum. The mixer is powered by a 3 horse power Wagner Electric Motor and is operated at a speed of 30 revolutions per minute.

- A 0.5 cubic foot mixer of the tilting drum type, which was designed and built at the University of Alberta as a scale model of the type of mixer used on the construction of the Grand Coulee Dam in Colorado. (See photo F.) The mixer is powered by a 1/3 horse power motor and is operated at 20 revolutions per minute.

Load Testing Machine

The load testing machine used in the laboratory for compressive strengths is a "Baldwin Southwark Tate-Emery" Testing Machine. (See photos G & H.) It is a hydraulic, reaction type, load testing machine of a maximum capacity of 200,000 pounds load. The loading is indicated by a pneumatic load indicator, having 3 scales as follows:

0 - 10,000 pounds - low scale

0 - 50,000 pounds - medium scale

0 -200,000 pounds - high scale

Photo E - Lancaster Mixer

Photo F - $\frac{1}{2}$ Cu. Foot - Tilting Drum Mixer

This allows for a choice of loading range so that maximum deflection of the needle, is obtained and thus greater accuracy in load values. The machine also has a load pacer which enables an adjustment of rate of loading to any desired number of pounds per second.

Hot Water Tank

This is a small electrically heated copper tank $9\frac{1}{2}$" x 21" x 18", surrounded by a galvanized metal box 16" x 28" x 25". The water is heated by means of 6 - 110 Volt "clamp-on", resistance type strap heaters connected in series, to be used with a 220 Volt outlet. The temperature was controlled by a liquid bulb-type thermostatic control switch. During use, however, this temperature regulator failed, and due to delay in replacement, a temperature sensitive liquid mercury "J" tube circuit breaker was used in conjunction with a relay switch. The "J" tube was found to give much better controlled temperatures, but inherently required more attention by the operator, since it was necessary to replace the temperature sensitive liquid for a change of temperatures. The unit is at present still equipped with this type of temperature control. (See photo J.)

Moist Room

The moist room available for moist curing is a cement plaster lined room 10' x 10' x 8'. Access is provided by a standard size door, and angle iron shelves provide storage space for cylinders. The temperature and humidity are maintained by regulation of hot and cold water lines leading to the vaporizer unit.

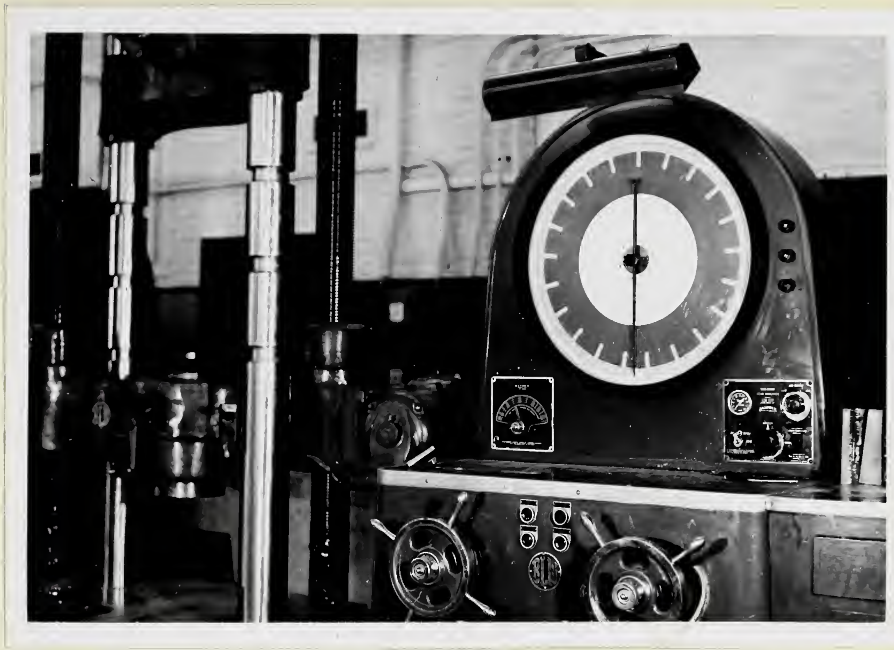


Photo G - Baldwin Testing Machine

Photo H - Testing Head of Baldwin Testing Machine

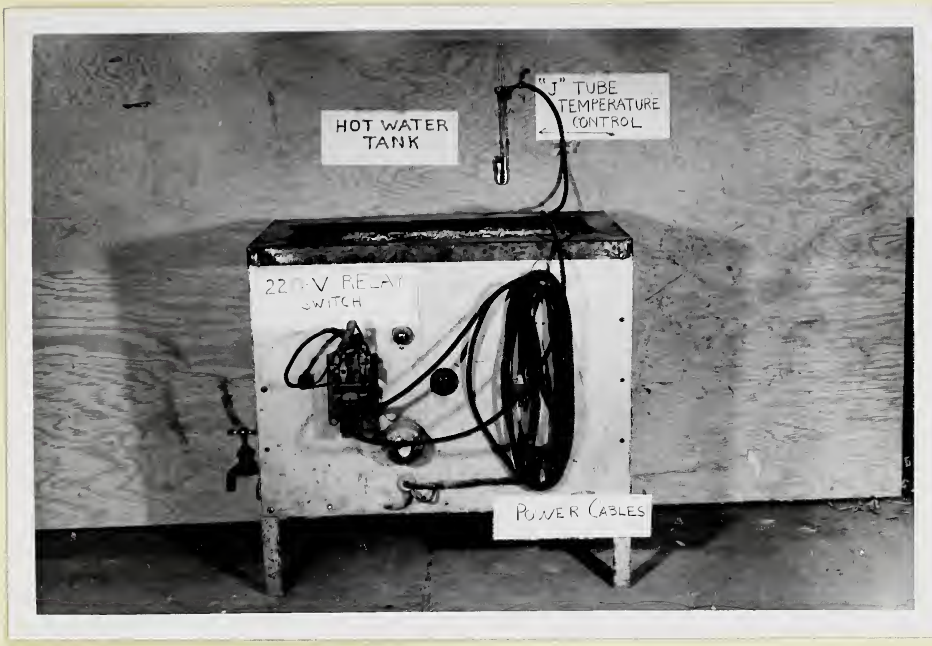


Photo J - Hot Water Tank

Photo K - Molds and Miscellaneous Equipment

Concrete Cylinder Molds

The concrete molds used were 4" x 8" metal cylinders, with a split wall, compressed together by a circular clamp, to make a tight joint. A metal base plate, sealed to the cylinder with molten sulphur, completed the units. (See photo K.)

In addition sealed molds were made by using a top and bottom plate with the standard cylindrical mold. The unit was clamped together by 4 - $\frac{1}{4}$" bolts at each corner of the plate. A seal on each end was obtained by using a steam rubber gasket slightly larger than the mold. Sulphur was also used to seal the longitudinal split, after the mold was compressed together, filled with mortar, and sealed by the base plate and top plate. (See photo K.)

Miscellaneous Equipment

1. Standard slump cone and bullet shaped rod.
2. Shovels.
3. Trowels.
4. Laboratory balance scales.
5. Drying ovens.
6. Various types of pans for weighing, drying, etc.
7. Electrically heated sulphur melting pots and molds for forming caps on the test cylinders.

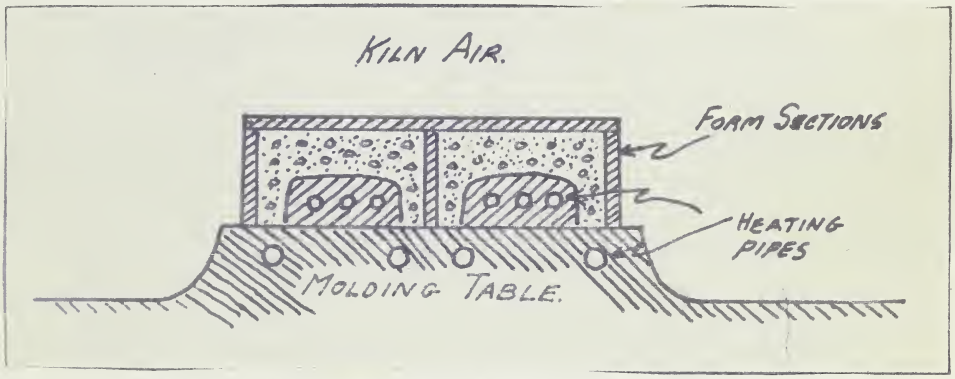
PART III

HEATED MOLD CURING INVESTIGATION

Introduction

In concrete manufacturing plants, precasting of concrete units are widely used for such construction units as floor beams, joists, bridge floor sections, concrete pipe, conduits, etc., with either pre-stressed or normal reinforcement.

Many such units are made in a "loaf" type mold, and when cured in a steam kiln would be heated on only 2 or 3 surfaces. (See sketch of a typical method of molding a probable section.)



There would be temperature gradients within the concrete, as the interior parts of the molds can only be heated by conduction through the concrete. A considerable advantage may result when such molds are heated internally, by such means as hot water or steam pipes.

There are several ways in which such a system could be used.

1. The top of the concrete in the mold may be exposed to a humid atmosphere in a steam curing kiln, and the mold heated as the temperature is raised in the kiln.

2. The top of the concrete in the mold may be exposed to kiln atmosphere and the mold maintained at a constant temperature, before and after placing of the concrete, and for duration of the curing period.
3. The mold may be sealed tight so as to retain water present in the mix during the complete curing period, with temperature being slowly raised to a maximum value in the same type of cycle as a steam cure method.
4. The molds may be sealed tight as in 3, but maintained at a constant temperature before and after molding the concrete, and for the duration of the curing period.

The first method would present no major difficulties providing there is a suitable curing atmosphere in the steam kiln. The vapor pressures of atmosphers in kiln and concrete, will be substantially the same if the mold heating does not raise the temperature of the concrete above the kiln temperature.[5]

The second method is obviously an impractical one unless mold temperatures are kept exceedingly low, since water would be removed from the concrete during the heating-up stages of the curing period by differences in vapor pressure resulting from a higher concrete temperature.

The third and fourth methods could have considerable merit, even when not used in conjunction with steam kilns, as the water present initially in the mix is prevented from being removed.

This investigation was made to explore the effect of heat applied to sealed molds and was carried out in two parts, firstly using constant temperature, and secondly using the same temperature

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[5] Part I, page 8

gradients that were used in steam curing cycles.

Procedure and Layout of Investigation

Section I - Constant Temperature Curing

The first part was begun in September and continued until December. It was designed as a preliminary to the actual steam curing investigation, to investigate the effect of concrete placed in preheated molds at various temperatures, as well as the effect of a waiting period before quickly heating the molds.

To simplify the apparatus and procedure, it was decided to utilize the hot water tank as a heating medium. The concrete would be placed in the sealed molds, described in Part II, and the molds heated by immersing them in the water tank. Since the capacity of the hot water tank was three sealed molds, the procedure was as follows:

> Five cylinders were cast at each mix; three sealed molds to be cured by heat, two open top molds for control cylinders to be cured in moist air in the moist curing room. Of the sealed molds, one was placed immediately in the hot water, one after a two hour waiting period, and the final one after a four hour waiting period. The water was maintained at a constant temperature. Twenty-four hours after mixing, the concrete cylinders were tested for compressive strength, which required that they be removed from the water tank one hour before testing time. One control cylinder was tested at 7 days and one tested at 28 days.

The temperatures of the water was maintained at 130, 150, 165, 180, 190 and 200 degrees F. Four mixes were made and cured at each of these temperatures, except for 180 and 200 degrees F., where only two mixes were made. This represented 20 mixes, or 100 cylinders cast and tested.

The mix was designed for 0.60 water ratio and a 2" slump. The aggregate used was "Elk Island Sand" and "O.K." Construction Company 1" gravel. Standard Exshaw Type I Portland Cement and ordinary domestic tap water were used. Moisture contents were obtained for sand and gravel immediately before mixing, so that the mix could be altered as required to obtain the 0.60 water cement ratio. Further moisture content samples were obtained from sand and gravel used in the mix, so that the actual water cement ratio could be computed.

The 0.5 cubic foot, tilting drum type mixer described in Part II, page 31 was used, with an 8 minute mixing time, measured after the mixer was charged with all the materials. The mixing procedure was to charge the mixer with sand, gravel and cement, and dry mix for one minute before adding the mixing water. Immediately after discharging the mixer a slump test was made by means of a standard slump cone, using three lifts rodded 25 times each. The slump was recorded, as well as descriptions of rodability and worability.

During each curing period a record of water temperature and one cylinder temperature were obtained by the use of thermocouples and the "Brown" temperature recorder.

Section II - Varying Temperature Curing

The second part was carried out in conjunction with the steam curing investigation. Two sealed molds were cast from the mix used in that investigation. They were subjected to the same waiting time and the same curing cycles. (See Procedure and Layout of Investigation, Part IV.) After the steaming cycle, the molds were removed and concrete cylinders stored in the laboratory air for thirteen days before being

tested for compressive strength. Moisture contents were obtained, for one cylinder of each pair, at the time of the compressive strength test.

The mix, as described in Part IV - Aggregate Tests and the Design Mix, was for 0.50 water cement ratio with a 3" slump. The aggregates used were Elk Island Sand, Alberta Concrete Products 1" coarse aggregate, Alberta Concrete Products $\frac{1}{2}$" aggregate. Exshaw Type I Portland Cement and normal domestic tap water were also used in the mix. The Lancaster type mixer was used with a five minute mixing time measured after all materials of the mix were introduced, and a slump test taken immediately after completion of mixing time.

This phase of the investigation was designed to compare results with those of the constant temperature cure method, to compare results with those of the steam curing investigation, and possibly to indicate the effectiveness of the curing atmosphere in the kiln. For a complete description of procedure of mixing and curing, aggregate tests and design mixes see Part IV - Steam Curing Investigation.

The compressive strength testing procedure was identical for both parts and was performed as follows:

The cylinders were capped with a sulphur and fire clay mixture to ensure square and level surfaces for uniform bearing pressure. A crossectional diameter was obtained by averaging two diameters measured at right angles to each other near the specimen midheighth. The load was applied at a constant rate of 20,000 pounds per minute.

<u>Aggregate Tests, Materials and Mix Designs</u>

The aggregates used in this investigation were obtained locally from stock piles in general use in the Edmonton area.

Section I - Constant Temperature Curing

The coarse aggregate used was that of O.K. Construction Company with a grading up to 1 inch. The physical properties of the aggregate are given in Table I and the grading is given in Table II.

The fine aggregate used was Elk Island pit run sand. The physical properties of the sand are given in Table I and the grading is given in Table III.

The cement used was Standard Exshaw cement Type I as supplied by Gormans Limited, Edmonton, Alberta.

Ordinary domestic tap water was used for mixing water.

Section II - Varying Temperature Curing

The aggregates, cement and mixing water used in mixes of Section II - Varying Temperature Heated Mold Curing, are completely described in Part IV - Aggregate Tests and Design Mixes.

TABLE I

Physical Properties of Aggregates

Material	Physical Properties			
	Absorption (24 Hr) % by weight	Specific Gravity		
		Bulk Sp. Gr.	Apparent Sp. Gr.	Bulk Sat. & Surf. dry
Coarse agg.	0.90	2.51	2.59	2.54
Elk Island Sand	1.0	2.60	2.66	2.62

TABLE II

Sieve Analysis of Coarse Aggregates

(O.K. Construction 1" Gravel)

Sieve Size	Wt. Retained Gms.	% Retained	Cumulative % Retained
1 1/2"	0	0	0
1"	418.0	2.7	2.7
3/4"	5375.0	34.2	36.9
3/8"	7610.0	48.5	85.4
#4	2040.0	13.0	98.4
Pan	270.0	1.6	100.0
Total	15713.0	100.0	

TABLE III

Sieve Analysis of Fine Aggregates

(Elk Island Sand)

Sieve Size	Wt. Retained Gms.	% Retained	Cumulative % Retained	A.S.T.M. Standards
#4	20.76	3.8	3.8	0-5
#8	51.48	9.5	13.3	
#14	65.55	12.0	25.3	20-55
#28	113.70	21.1	46.4	
#48	198.49	36.6	83.0	70-90
#100	66.85	12.3	95.3	90-98
Pan	23.84	4.7	100.0	
Total	531.75	100.00	267.1	

Fineness Modulus - 2.67

% material passing #200 sieve - 2.8%.

Organic impurities - #2 color - (good for most concrete work)

Mix Designs

Section I - Constant Temperature Heated Molds

All mixes used in this portion of the investigation were designed for a water cement ratio of 0.60 ($5\frac{1}{2}$ bags of cement per cubic yard.) The slump was designed for 2".

Materials

Cement - Exshaw Standard Portland Cement Type I

specific gravity 3.13.

Sand - Elk Island (41% of total aggregate)

Specific gravity 2.62 - absorption - 1.0%

Fineness Modulus 2.67

Gravel - O.K. Construction

Specific gravity 2.54 - absorption - 0.9%

Maximum size 1"

Cement content - $5\frac{1}{2}$ bags per cubic yard

Slump - 2 inch

Determination of Trial Mix Proportions

Water content - 290 pounds per cubic yard

Cement content - $\frac{290}{0.60} = 484$ pounds per cubic yard

$= 5.52$ bags per cubic yard

Absolute volume of water and cement $= \frac{291}{62.4} + \frac{484}{3.13 \times 62.4} =$

$4.68 + 2.48 = 7.15$ cubic feet per cubic yard.

Absolute volume of total aggregate $= 27 - 7.15 = 19.85$ cubic feet per cubic yard.

Absolute volume of sand = 0.41 x 19.85 = 8.14 cubic feet per cubic yard

Absolute volume of gravel = 19.85 - 8.14 = 11.71 cubic feet per cubic yard

Sand content = 8.14 x 2.62 x 62.4 = 1290 pounds per cubic yard

Gravel content = 11.71 x 2.54 x 62.4 = 1850 pounds per cubic yard

Total Mix Proportions

290 pounds water; 484 pounds cement; 1290 pounds sand; 1850 pounds gravel:

$$\frac{290}{484} : \frac{484}{484} : \frac{1290}{484} : \frac{1850}{484}$$

0.60 : 1 : 2.67 : 3.83 (by weight)

Mix Proportions for 50 pound Batch

cement - 6.20 pounds

water - 3.48 pounds

sand - 16.63 pounds

gravel - 23.91 pounds

Section II - Varying Temperature Heated Molds

For complete details of mix design used in this section see Part IV - Steam Curing Investigation - Aggregate Tests and Mix Designs.

The mix used was for 7 bags of cement per cubic yard and a water cement ratio of 0.50 - with a 3" slump. Alberta Concrete Products 1" max. size aggregate and $\frac{1}{2}$" maximum size aggregates, and Elk Island sand were used.

Test Results and Discussions

Section I - Constant Temperature Heated Molds

The concrete mix data for 7 and 28 day moist cure compressive strength results are given in Table IV. The strength values are of a single cylinder tested from each mix.

Figure 5 is a plot of water-cement ratio versus 7 day compressive strengths and 28 day compressive strengths. An examination of Table IV and Figure 5 shows that there is very poor correlation between the water-cement ratio and compressive strengths for 7 days and 28 days as well as between 7 and 28 day strengths. Two factors are believed responsible for such discrepancies. Firstly the small tilting drum mixer was constructed and operated in such a manner that material piled up on the mixing shelves or blades. This material consisted mainly of a cement and water mixture and thus tended to give variations in cement content from mix to mix. In addition, the mixing action is not believed vigorous enough. Secondly large variations in test values are believed due to improper technique in testing, in that a separate self-centering steel block was not used in conjunction with the large ball and socket jointed bearing plate incorporated in the crosshead of the testing machine. When the 4 x 8 standard test cylinders are tested without using a separate self-centering ball block, eccentricity in loading is possible, since considerable effort would be required to align the bearing block of the crosshead with the top of the test cylinder, due to the large diameter of the ball and socket fitting. The eccentricity is believed by the writer to

be the major factor causing the very poor correlation between water-cement ratio and compressive strengths. Unfortunately this effect was not realized until after the testing procedure was completed. However in subsequent testing, a self-centering ball block was used on top of the test cylinders, and much better correlation in strength results was obtained. (See results Steam Cure Investigation Part IV).

The 24 hour strength results of cylinders cured at various temperatures and preset periods are given in Table V. For each curing temperature and preset period the individual strength value, and its percentage of 7 and 28 day moist cure strengths, is given. The average strength expressed as a percentage of 7 and 28 day moist cure strengths for each curing temperature and preset period is also given. In this manner variations in strengths due to variations in computed water-cement ratios is minimized.

The average compressive strength versus curing temperature plot of the preset period of 0 hours, 2 hours and 4 hours is given in figure 6.

Figure 7 is a plot of average compressive strength versus preset period time for the temperatures of 130, 150, 165, 180, 190 and 200 degrees F.

A comparison of 7 and 28 day moist cure results for both figures 6 and 7 show a variation due to variations in strengths as shown in figure 5. Generally both figures indicate an advantage in allowing a preset period before curing at higher temperatures. This is to be expected since the preset period allows the hydration process to begin before application of heat. Another general trend is also

indicated by the figures 6 and 7, in that for a given preset period the resulting strengths increase slightly for an increase in cure temperature up to about 185 degrees F., after which there is no gain in strengths. An interesting feature is indicated in figure 6, in that strengths for curing temperature of 165 degrees F. are considerably lower than other temperatures. While an accumulative effect of erroneous values could cause such a result, the writer believes that it does not explain the phenomenon, because it is doubtful that four mixes would have such extremely low values, especially since two of the mixes were made 30 days after the other two.

The rapid initial heating up and final cooling down when the sealed molds were immersed in the hot water bath at start of curing period and removed at the end of the period probably tended to exaggerate the variation in strengths.

Section II - Varying Temperature Heated Molds

Table VI is an abbreviated table of concrete mix data for the sealed molds and compressive strength at 7 and 28 days for the moist cured control cylinders. For a more detailed table of mix data see Table XIII - Steam Cure Investigation, where also given is figure 14 the water-cement ratio versus compressive strength plot for the mixes.

Table VII gives the strength results of the sealed molds for 3 curing cycles and 3 temperatures. The results are given as actual numerical values as well as percentages of 7 day and 28 day moist cure strengths. For a definition of the three curing cycles I, II and III see Part IV - Steam Curing Investigation.

Figure 8 is a plot of the 14 day compressive strengths (24 hours steam and 13 days laboratory air) expressed as percentages of 7 and 28 day moist cure strengths versus curing temperatures. These curves indicate that where steam treatment was followed by 13 days storage in laboratory air, the curing temperature and type of curing cycle employed, have relatively little effect on the resulting strengths except at the higher temperatures where slight decreases can be expected. This effect results from the fact that at the higher temperatures, adverse conditions affecting hydration, tend to reduce the subsequent potential strength gains during storage.

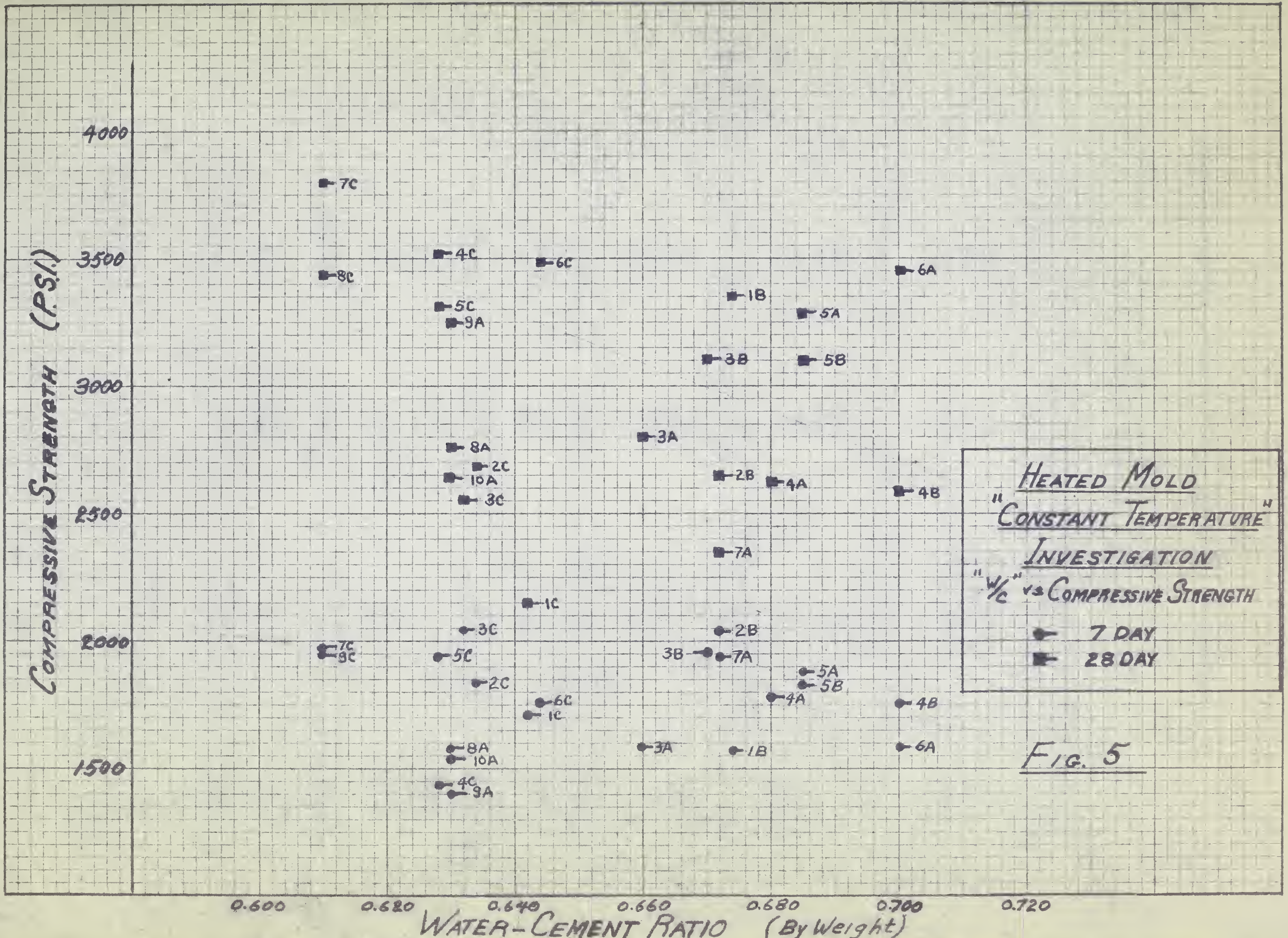
Figures 8 and 9 give comparisons of Constant Temperature and Varying Temperature Heated Mold Curing conditions, expressed as percentages of 7 and 28 day moist cure strengths respectively.

CONCRETE MIX DATA - HEATED MOLDS - CONSTANT TEMPERATURE

Mix No.	Date Cast	Mix Proportions per cubic yards: Cement lbs.	Cement bags	Sand lbs.	Gravel lbs.	Water lbs.	W/C	Slump Ins.	Workability	7 day Comp. Str.	28 day Comp. Str.
3A	Oct 12	482	$5\frac{1}{2}$	1280	1850	319	0.661	3.5	G	1580	2800
4A	Oct 17	482	$5\frac{1}{2}$	1280	1820	328	0.680	3.5	G	1690	2620
5A	Oct 18	482	$5\frac{1}{2}$	1278	1830	330	0.685	2.5	F	1880	3280
6A	Oct 20	482	$5\frac{1}{2}$	1275	1820	338	0.702	3.5	G	1590	3455
7A	Oct 23	482	$5\frac{1}{2}$	1282	1822	324	0.672	2.5	F	1940	2340
8A	Oct 24	482	$5\frac{1}{2}$	1268	1855	304	0.630	3.5	G	1575	2760
9A	Oct 25	482	$5\frac{1}{2}$	1270	1860	320	0.630	2.5	F	1400	3240
10A	Oct 26	482	$5\frac{1}{2}$	1272	1855	320	0.630	2.75	F	1530	2630
1B	Oct 27	482	$5\frac{1}{2}$	1280	1820	325	0.674	3.25	G	1570	3355
2B	Oct 30	482	$5\frac{1}{2}$	1280	1832	324	0.672	3.25	G	2045	2640
3B	Oct 31	482	$5\frac{1}{2}$	1270	1820	323	0.671	3.5	G	1950	3100
4B	Nov 1	482	$5\frac{1}{2}$	1275	1820	338	0.702	3.5	G	1765	2580
5B	Nov 2	482	$5\frac{1}{2}$	1270	1820	330	0.685	3.75	G	2875	3100

Table IV - Cont'd

Mix No.	Date Cast	Cement lbs.	Cement bags	Sand lbs.	Gravel lbs.	Water lbs.	W/C	Slump Ins.	Workability	7 day Comp. Str.	28 day Comp. Str.
		Mix Proportions per cubic yards									
1C	Nov 3	482	$5\frac{1}{2}$	1290	1845	309	0.642	2.75	G	1710	2140
2C	Nov 10	482	$5\frac{1}{2}$	1290	1850	305	0.634	2.25	F	1835	2680
3C	Nov 13	482	$5\frac{1}{2}$	1290	1845	304	0.632	2.75	G	2045	2550
4C	Nov 14	482	$5\frac{1}{2}$	1287	1850	302	0.628	2.25	F	1410	3520
5C	Nov 16	482	$5\frac{1}{2}$	1291	1850	302	0.628	2.25	F	1945	3310
6C	Nov 17	482	$5\frac{1}{2}$	1287	1845	310	0.644	2.50	G	1760	3480
7C	Nov 20	482	$5\frac{1}{2}$	1290	1855	294	0.610	2.75	G	1960	3430
8C	Nov 21	482	$5\frac{1}{2}$	1290	1860	294	0.610	2.5	G	1950	3800



HEATED MOLD
"CONSTANT TEMPERATURE"
INVESTIGATION
"W/C" vs COMPRESSIVE STRENGTH
7 DAY
28 DAY
COMPRESSIVE STRENGTH (P.S.I.)
4000
3500
3000
2500
2000
1500
0.600
0.620
0.640
0.660
0.680
0.700
0.720
WATER-CEMENT RATIO (By Weight)
7C
8C
4C
5C
9A
6C
6A
1B
5A
3B
5B
3A
8A
2C
10A
3C
2B
4A
4B
7A
1C

FIG. 5

TABLE V

STRENGTH RESULTS - HEATED MOLD - CONSTANT TEMPERATURE

(24 Hour)

CURE A - (0 hrs preset period)

Temp.	Specimen Number	Comp. Str. (psi)	% 7 Day Comp. Str.	% 28 Day Comp. Str.
130° F.	1C1	1110	65.0	52.0
	2C1	1380	75.3	51.5
	5C1	1000	51.5	30.0
	6C1	980	55.6	28.2
	Average	1120	61.8	40.4
150° F.	3A1	893	56.5	31.9
	4A1	893	52.8	34.0
	3C1	1230	60.0	48.8
	4C1	1140	80.8	32.4
	Average	1015	62.5	36.8
165° F.	5A1	975	51.8	29.5
	6A1	1020	64.3	29.6
	7C1	890	45.4	26.0
	8C1	1250	64.2	32.9
	Average	1035	56.4	29.5
180° F.	7A1	1380	71.2	59.0
	8A1	940	59.6	34.0
	Average	1160	65.4	46.5
190° F.	9A1	1200	86.0	37.0
	10A1	1730	113.0	67.0
	3B1	1165	60.0	37.6
	4B1	945	53.5	36.6
	Average	1260	78.1	44.5
200° F.	1B1	1330	84.8	39.7
	2B1	1200	58.6	45.5
	Average	1265	71.7	47.6

TABLE V - Cont'd

STRENGTH RESULTS - HEATED MOLD - CONSTANT TEMPERATURE
(24 Hour)

Cure B - (2 hrs preset period)

Temp.	Specimen Number	Comp. Str. (psi)	% 7 Day Comp. Str.	% 28 Day Comp. Str.
130° F.	1C2	1290	75.5	60.3
	2C2	1110	60.3	41.5
	5C2	1085	55.8	32.8
	6C2	1255	71.3	36.0
	Average	1185	65.8	42.7
150° F.	3A2	1080	68.5	38.6
	4A2	1140	67.4	43.5
	3C2	1320	64.5	51.8
	4C2	1330	94.3	37.8
	Average	1220	73.7	42.9
165° F.	5A2	995	62.5	30.3
	6A2	1175	74.0	33.2
	7C2	1080	55.2	31.5
	8C2	1675	86.0	44.0
	Average	1230	69.4	24.8
180° F.	7A2	1300	68.0	55.6
	8A2	1100	70.0	40.0
	Average	1200	69.0	47.8
190° F.	9A2	1400	100.0	43.2
	10A2	1293	84.6	48.2
	3B2	1215	62.3	39.2
	4B2	870	49.3	33.8
	Average	1200	74.0	41.1
200° F.	1B2	1400	88.3	41.8
	2B2	1220	59.6	46.2
	Average	1310	73.9	44.0

TABLE V - Cont'd

STRENGTH RESULTS - HEATED MOLD - CONSTANT TEMPERATURE
(24 Hour)

CURE C - 4 hrs preset period

Temp.	Number	Comp. Str. (psi)	% 7 Day Comp. Str.	% 28 Day Comp. Str.
130° F.	1C3	1160	67.8	54.2
	2C3	1290	70.4	48.2
	5C3	1185	61.0	35.4
	6C3	1280	72.8	36.8
	Average	1230	68.0	43.6
150° F.	3A3	920	58.3	32.8
	4A3	1200	71.0	45.8
	3C3	1510	74.0	58.2
	4C3	1325	94.0	37.6
	Average	1240	74.3	43.6
165° F.	5A3	1100	58.5	33.6
	6A3	1050	66.0	29.5
	7C3	980	45.4	26.0
	8C3	1360	69.7	35.8
	Average	1125	59.9	31.2
180° F.	7A3	1720	88.6	73.5
	8A3	1099	69.9	40.0
	Average	1410	79.2	56.7
190° F.	9A3	1240	88.6	38.3
	10A3	1550	101.0	59.0
	3B3	1100	56.5	35.5
	4B3	1145	65.0	44.5
	Average	1260	77.8	44.3
200° F.	1B3	1300	83.0	38.8
	2B3	1120	54.8	42.4
	Average	1210	68.9	40.6

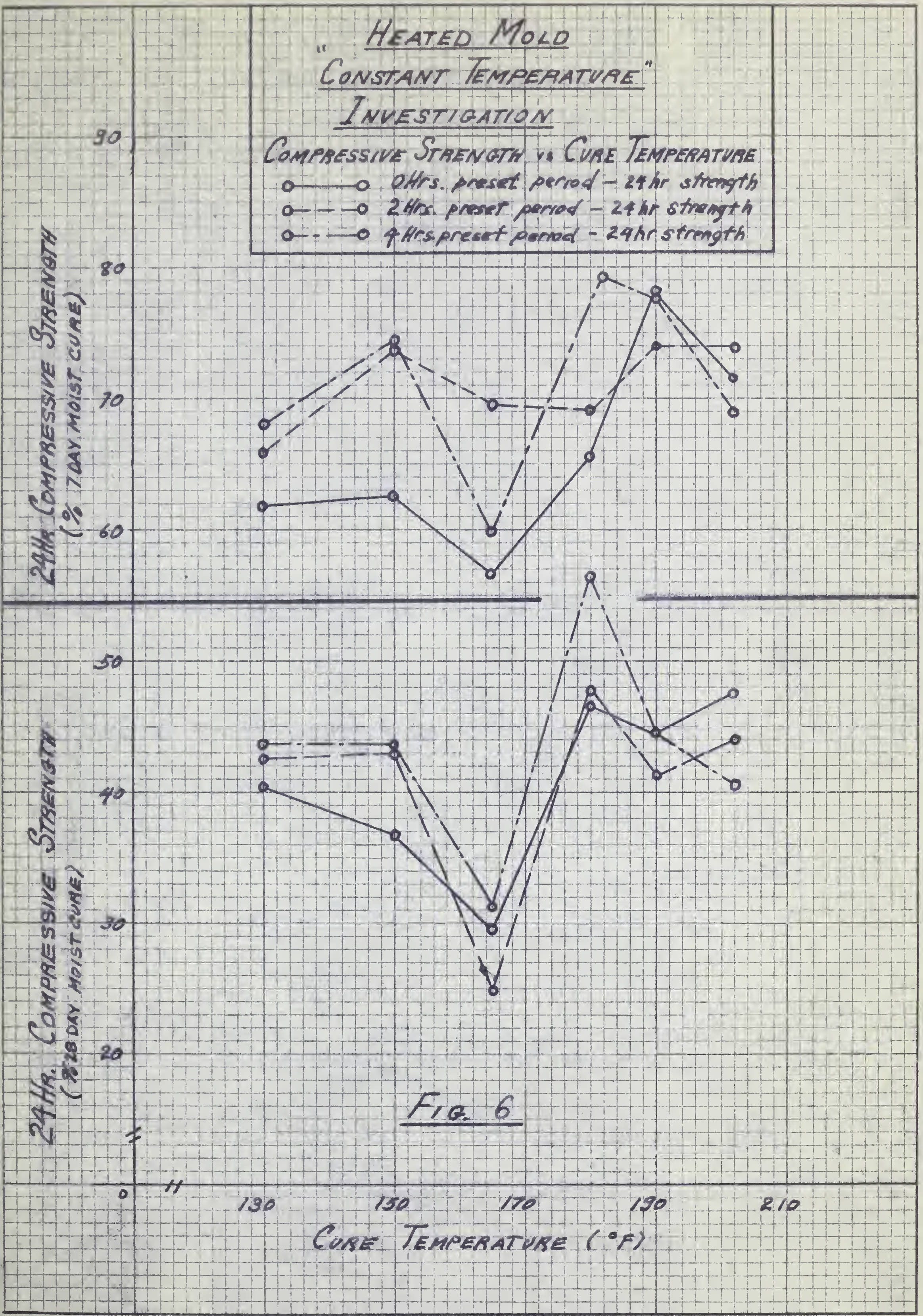

HEATED MOLD
"CONSTANT TEMPERATURE"
INVESTIGATION
COMPRESSIVE STRENGTH vs CURE TEMPERATURE
0 Hrs. preset period - 24 hr strength
2 Hrs. preset period - 24 hr strength
4 Hrs. preset period - 24 hr strength
24 HR. COMPRESSIVE STRENGTH (% 7 DAY MOIST CURE)
24 HR. COMPRESSIVE STRENGTH (% 28 DAY MOIST CURE)
90
80
70
60
50
40
30
20
0
130
150
170
190
210
CURE TEMPERATURE (°F)

FIG. 6

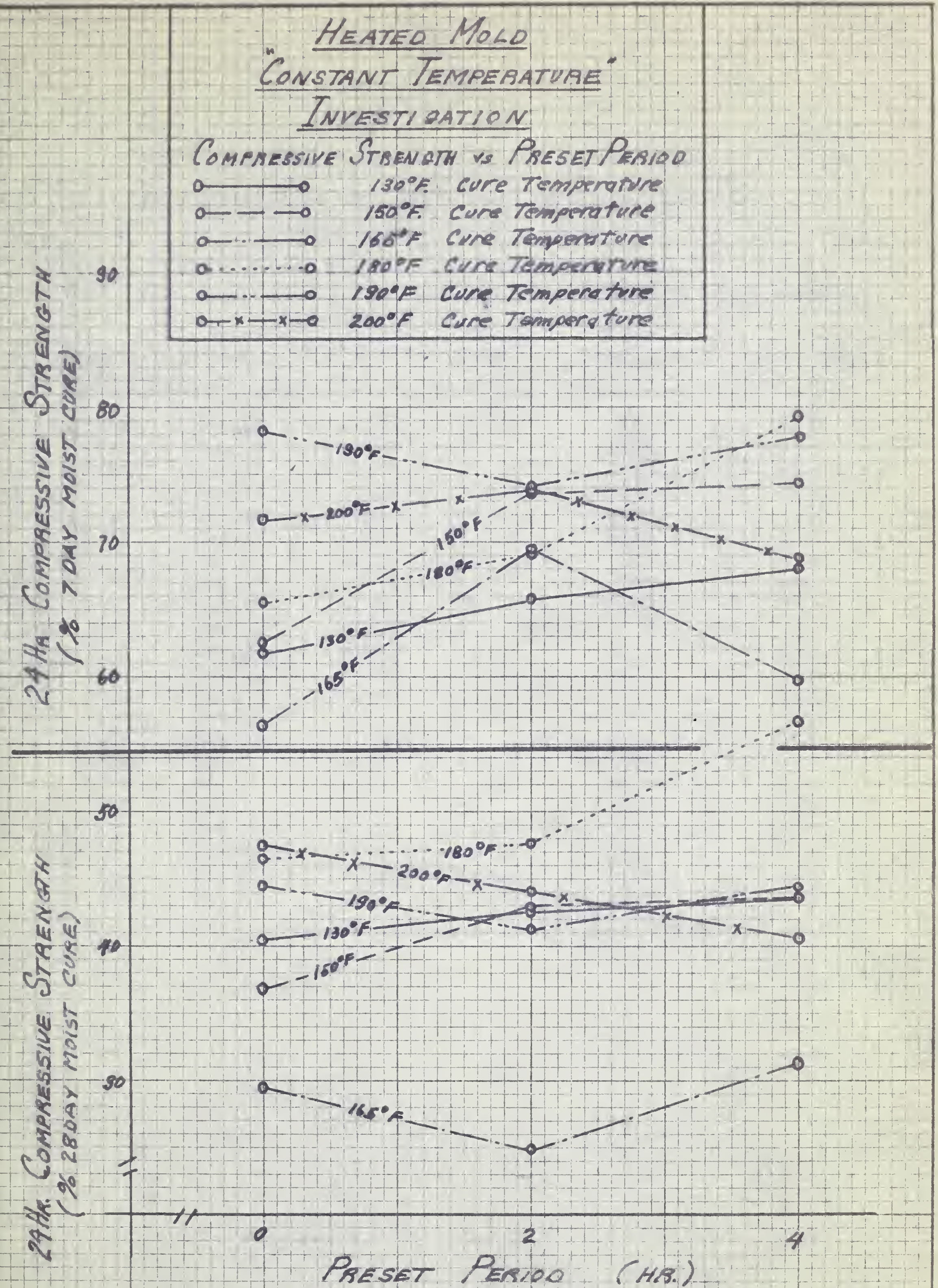

HEATED MOLD
"CONSTANT TEMPERATURE"
INVESTIGATION
COMPRESSIVE STRENGTH vs PRESET PERIOD
130°F Cure Temperature
150°F Cure Temperature
165°F Cure Temperature
180°F Cure Temperature
190°F Cure Temperature
200°F Cure Temperature
24 HR. COMPRESSIVE STRENGTH (% 7 DAY MOIST CURE)
24 HR. COMPRESSIVE STRENGTH (% 28 DAY MOIST CURE)
90
80
70
60
50
40
30
0
2
4
190°F
200°F
150°F
180°F
130°F
165°F
PRESET PERIOD (HR.)

FIG 7

TABLE VI

CONCRETE MIX DATA - HEATED MOLD - VARYING TEMPERATURE

(Abbreviated From Table XII - Steam Cure Investigation)

x - average of two cylinders

Mix No.	Date Cast	W/C	Slump	x 7 Day Comp. Str.	x 28 Day Comp. Str.
1D	Jan 15	0.528	3"	2195	3730
2D	Jan 17	0.507	3"	2965	4355
3D	Jan 18	0.512	3"	2785	4365
4D	Jan 19	0.504	2 3/4"	3235	4785
5D	Jan 22	0.510	3"	3015	4245
6D	Jan 24	0.505	3 1/2"	2705	4085
7D	Jan 25	0.510	3"	2625	4270
8D	Jan 26	0.495	2 3/4"	3360	4855
9D	Jan 27	0.500	3"	3380	4915
10D	Feb 1	0.498	3"	2750	4900
11D	Feb 2	0.495	2 1/2"	3165	4995
12D	Feb 5	0.500	2 3/4"	3225	5210
13D	Feb 7	0.498	2 1/2"	3210	5200
14D	Feb 8	0.510	2 3/4"	3045	4900
15D	Feb 9	0.505	2"	3310	4635
16D	Feb 12	0.508	2 1/2"	3275	4730
17D	Feb 14	0.506	1 3/4"	3510	5275
18D	Feb 15	0.498	2"	3470	4885
19D	Feb 16	0.513	2 1/4"	3200	4550
20D	Feb 19	0.505	2 1/4"	3305	4710
21D	Feb 21	0.502	2 1/2"	3170	4780
22D	Feb 28	0.498	2 1/4"	3495	5200

TABLE VII

STRENGTH RESULTS - HEATED MOLD - VARYING TEMPERATURE

CURE METHOD D - (sealed molds - 24 hrs. steam & 13 days lab. air)
(age at test - 14 days)

CYCLE NO. I

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	22D11	-	4480	86.5	128.0
	22D12	-	4225	81.2	121.0
	3D11	3.0	3320	76.0	119.0
	3D12	-	3210	73.5	110.0
	Average		3810	79.3	119.5
160° F.	2D11	2.5	3770	86.5	127.0
	2D12	-	3730	85.5	125.8
	4D11	2.3	3650	76.2	113.0
	4D12	-	3370	70.5	104.0
	Average		3630	79.7	117.4
185° F.	5D11	2.3	3430	81.8	113.8
	5D12	-	3100	73.2	103.0
	6D11	1.9	3140	76.8	116.0
	6D12	-	2700	66.1	100.0
	Average		3090	74.5	108.2

TABLE VII - Cont'd

STRENGTH RESULTS - HEATED MOLD - VARYING TEMPERATURE

CURE METHOD D - Cont'd

CYCLE II

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	12D11	2.6	4100	78.6	127.1
	12D12	-	3870	74.3	120.0
	13D11	2.6	4160	80.0	133.5
	13D12	-	3820	73.4	131.0
	Average		3990	76.6	127.9
160° F.	9D11	2.4	4150	84.4	123.0
	9D12	-	4000	813.	118.4
	21D11	3.8	4220	88.3	133.0
	21D12	-	4160	87.0	131.0
	Average		4130	85.2	126.3
185° F.	7D11	2.4	3330	78.0	126.8
	7D12	-	3100	72.6	118.0
	8D11	2.3	3620	74.5	107.8
	8D12	-	3600	74.2	107.0
	Average		3390	74.3	114.6

TABLE VII - Cont'd

STRENGTH RESULTS - HEATED MOLD - VARYING TEMPERATURE

CURE METHOD D - Cont'd

CYCLE III

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	19D11	3.0	3900	85.8	107.0
	19D12	-	3920	86.2	144.6
	20D11	3.6	4160	88.4	126.0
	20D12	-	4140	88.0	125.6
	Average		4030	87.1	125.8
160° F.	17D11	2.5	4480	83.2	127.5
	17D12	-	4200	79.7	120.0
	18D11	2.3	4020	82.5	115.8
	18D12	-	4060	83.0	117.0
	Average		4190	82.1	120.1
185° F.	14D11	2.1	3610	73.7	118.3
	14D12	-	3720	75.8	122.0
	15D11	2.2	4290	92.6	129.3
	15D12	-	4430	96.0	134.0
	Average		4015	84.0	126.0

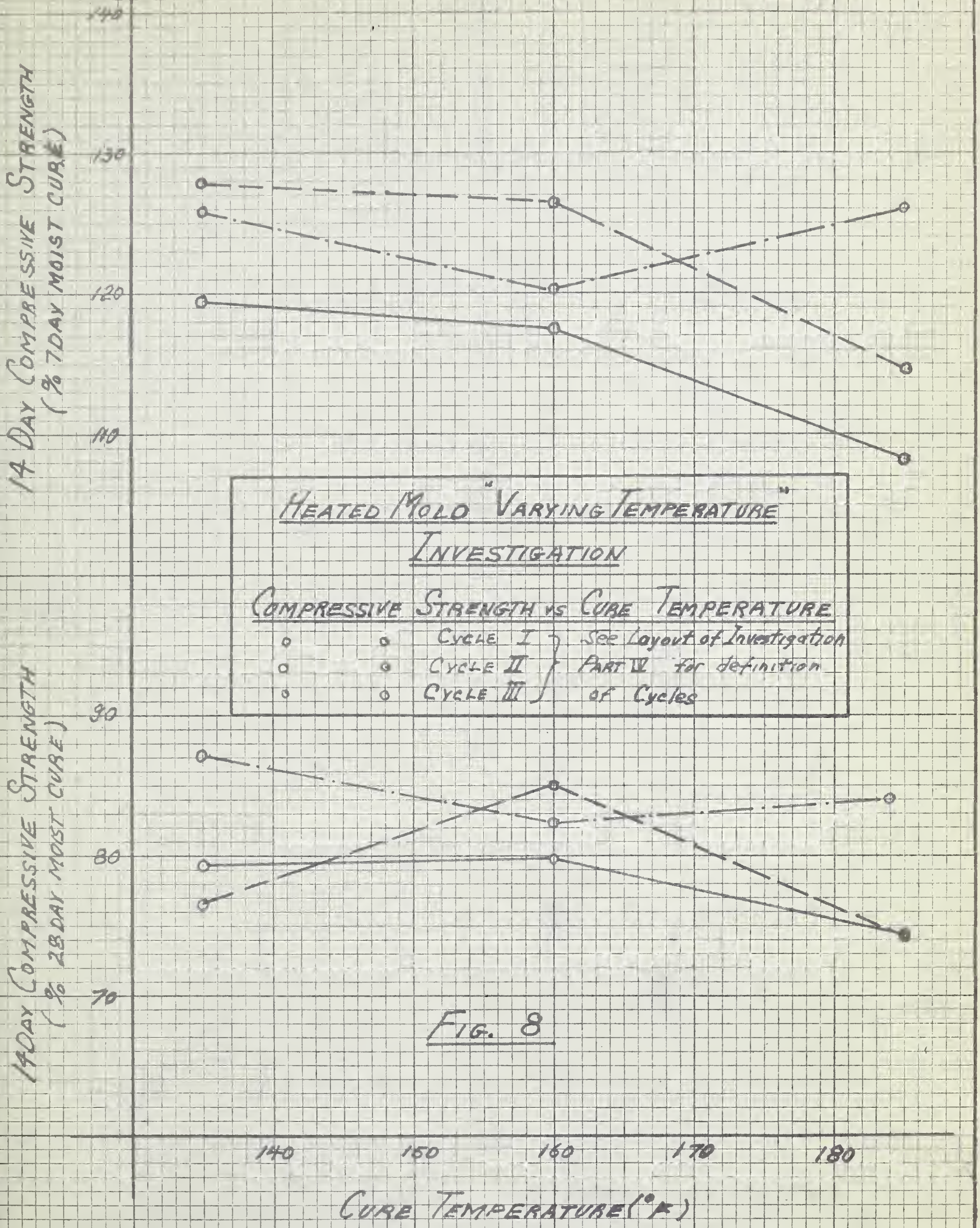

14 Day Compressive Strength
(% 7 Day Moist Cure)
14 Day Compressive Strength
(% 28 Day Moist Cure)
140
130
120
110
90
80
70
140
150
160
170
180
Cure Temperature (°F)
Heated Mold "Varying Temperature" Investigation
Compressive Strength vs Cure Temperature
Cycle I
Cycle II
Cycle III
See Layout of Investigation Part IV for definition of Cycles

Fig. 8

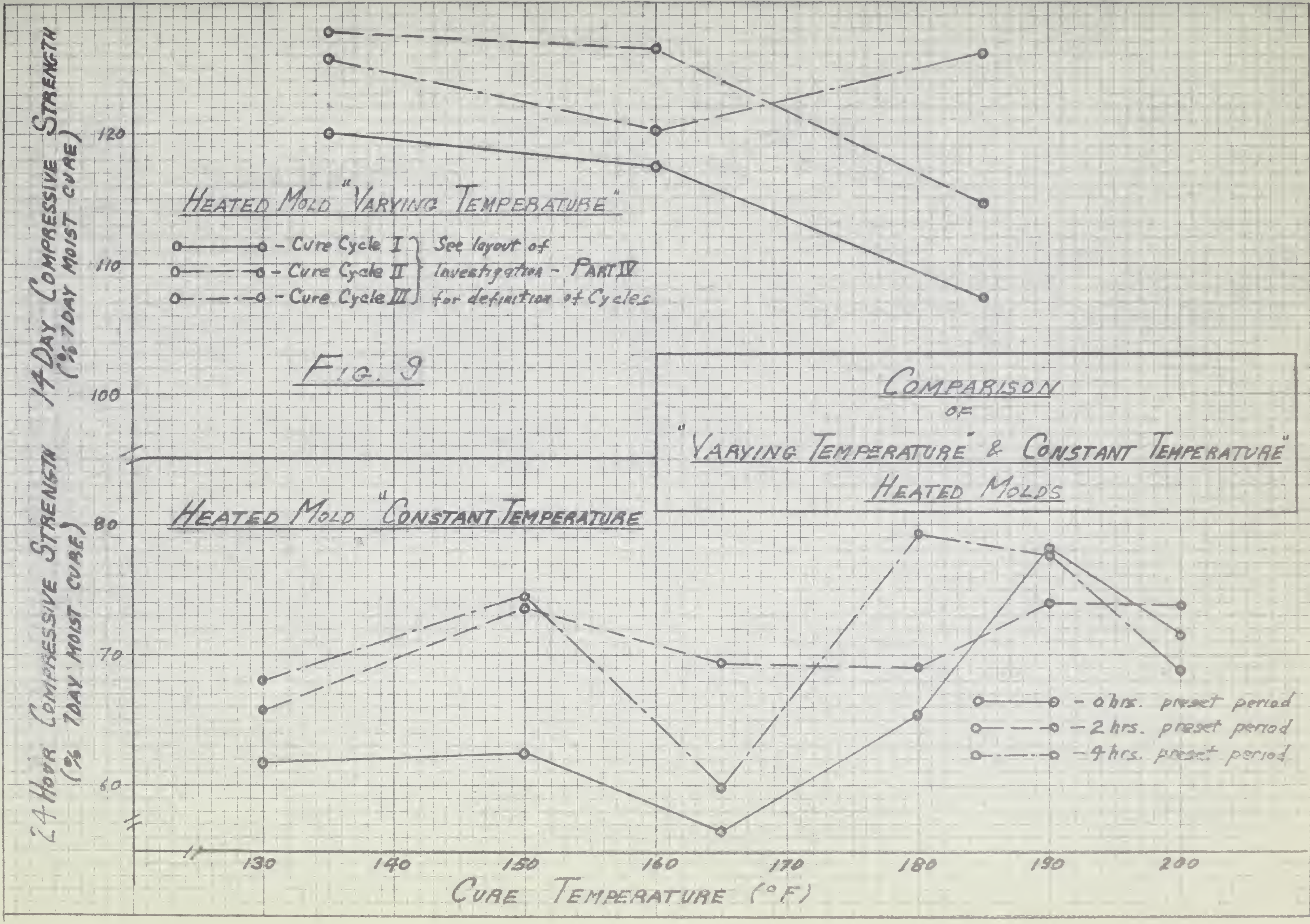

14 Day Compressive Strength (% 7 Day Moist Cure)
24 Hour Compressive Strength (% 7 Day Moist Cure)
120
110
100
80
70
60
Heated Mold "Varying Temperature"
- Cure Cycle I
- Cure Cycle II
- Cure Cycle III
See layout of Investigation - Part IV for definition of Cycles
Comparison of "Varying Temperature" & "Constant Temperature" Heated Molds
Heated Mold "Constant Temperature"
- 0 hrs. preset period
- 2 hrs. preset period
- 4 hrs. preset period
130
140
150
160
170
180
190
200
Cure Temperature (°F)

Fig. 9

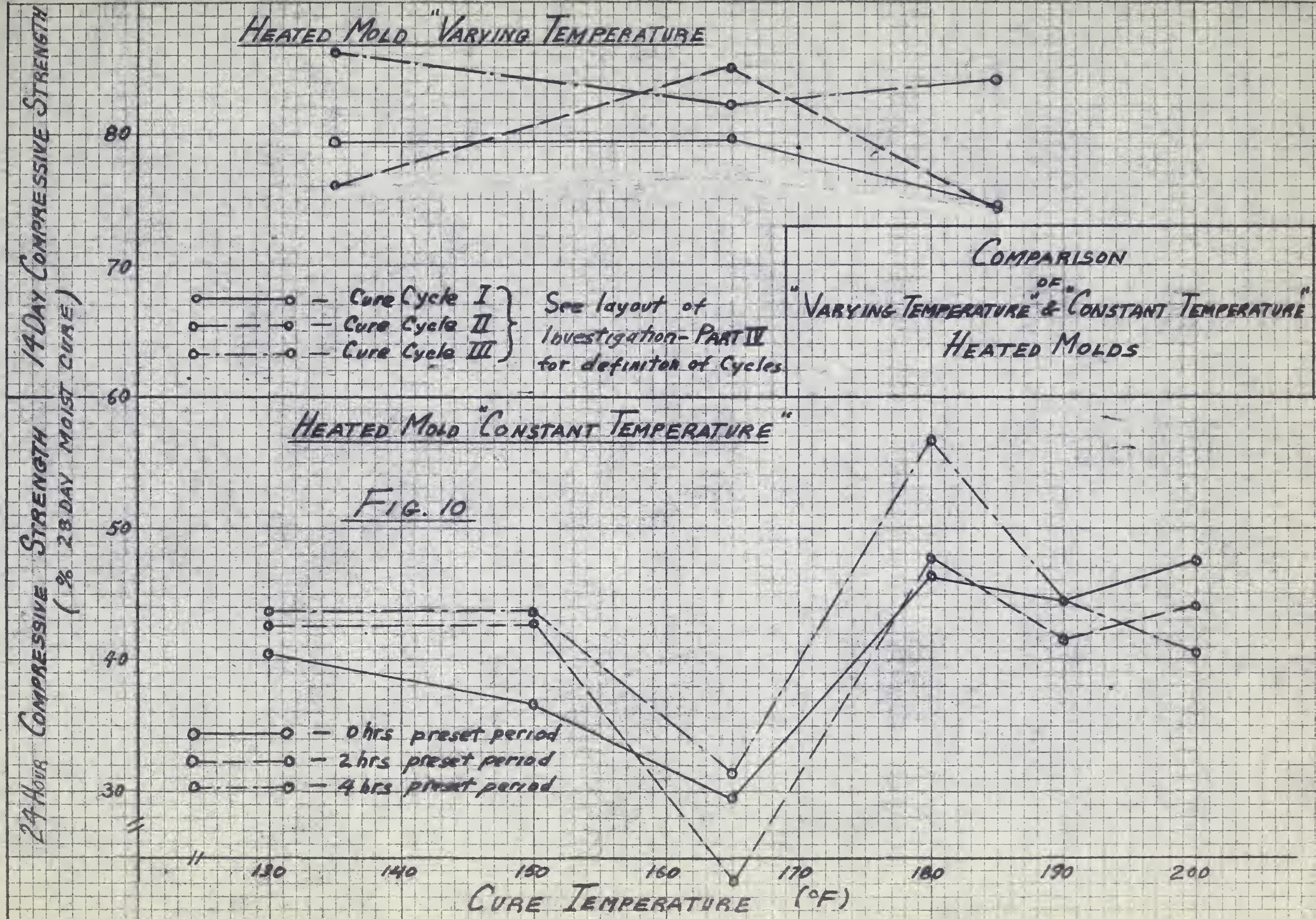

HEATED MOLD "VARYING TEMPERATURE
14 DAY COMPRESSIVE STRENGTH
24 HOUR COMPRESSIVE STRENGTH
(% 28 DAY MOIST CURE)
80
70
60
50
40
30
– Cure Cycle I
– Cure Cycle II
– Cure Cycle III
See layout of
Investigation - PART IV
for definiton of Cycles
COMPARISON
OF
"VARYING TEMPERATURE" & "CONSTANT TEMPERATURE"
HEATED MOLDS
HEATED MOLD "CONSTANT TEMPERATURE"
– 0 hrs preset period
– 2 hrs preset period
– 4 hrs preset period
130
140
150
160
170
180
190
200
CURE TEMPERATURE (°F)

FIG. 10

Summary of Conclusions

1. Generally there is an advantage in allowing a preset period of 2 - 6 hours before subjecting the fresh concrete to a curing program.
2. A slight increase in 24 hour strengths is obtained as the curing temperature is increased until a temperature of about 180 degrees F. is reached.
3. The temperatures used during a curing program have little effect on the resulting strengths when a subsequent storage time of 13 days is employed, except where temperatures are in the vicinity of 185 degrees F., where slight reductions in resulting strengths can be expected.
4. Too rapid time-temperature gradients during curing probably have adverse effects on the resulting strengths.

PART IV

STEAM CURING INVESTIGATION

Introduction

This investigation was designed to explore the effect of temperature on the compressive strength of concrete, during elevated temperature curing, by subjecting test cylinders to three different steam curing cycles, operating at three different maximum temperatures.

The major factors affecting compressive strengths of concrete, when cured by elevated temperatures are:

1. Water content in pounds per cubic yard.
2. Cement content in pounds per cubic yard.
3. Strength properties of materials used in the concrete mix.
4. Time elapsed at time of test.
5. Moisture content of concrete at the time of test.
6. Type of Curing - which is affected by:
    (a) moisture conditions of curing atmosphere.
    (b) rate of temperature rise, maximum temperatures obtained during curing period and time elapsed before application of heat.

In order to study the effect of temperature during curing, one must reduce the effect of all the other factors on the compressive strength to a minimum.

The first two factors can be combined together and expressed as the water-cement ratio. It has been shown, and is a well known fact that "For plastic mixtures using sound and clean aggregates, the strength and other desirable properties of concrete, under given job conditions vary inversely as the net quantity of mixing water used per sack of cement".[6]

Thus for a given water-cement ratio, given total quantity of cement per cubic yard, and given aggregates, the compressive strength will be constant when cured and tested under given constant conditions. If then concrete is produced with a water-cement ratio held constant, using materials each from a single source and job lot, and cured under constant moisture conditions, but with various time and temperature treatments, the resulting variations in compressive strengths can be assumed due to the conditions of time and temperature.

This assumption is the basis of procedure and layout in this part of the investigation.

6
The Water-Cement Ratio - Compressive Strength Law.
First enunciated by D. Abhrams.

Layout of Investigation

In this investigation nine conditions of steam curing were used. They consisted of three basic types of curing cycles (as outlined in Part II, page 10), each operated so that maximum temperatures 135, 160 and 185 degrees F. respectively were obtained. A presetting or waiting period of approximately five hours after mixing was allowed before concrete cylinders were subjected to the steam cure. An outline of each cycle and the three temperature ranges is given below:

Cycle I

135 Degrees F. - a constant time-temperature rise from 75 degrees to 135 degrees F. over a period of 1 hour - followed by a constant temperature of 135 degrees F. maintained for 16 hours - a constant time-temperature drop from 135 degrees F. to 75 degrees F. over a period of 5 hours.

160 Degrees F. - a constant time-temperature rise from 75 degrees F. to 160 degrees F. over a period of $1\frac{1}{2}$ hours - followed by a constant temperature of 160 degrees F. maintained for 15 hours - a constant time-temperature drop from 160 degrees F. to 75 degrees F. over a period of $5\frac{1}{2}$ hours.

185 Degrees F. - a constant time-temperature rise from 75 degrees F. to 185 degrees F. over a period of 2 hours - followed by a constant temperature of 185 degrees F. maintained for 13 hours - a constant time-temperature drop from 185 degrees F. to 75 degrees F. over a period of 7 hours.

Cycle II

135 Degrees F. - a constant time-temperature rise from 75 degrees F. to 135 degrees F. over a period of 11 hours - followed by a constant

time-temperature drop from 135 degrees F. to 75 degrees F. over a period of 11 hours.

160 Degrees F. - a constant time-temperature rise from 75 degrees F. to 160 degrees F. over a period of 11 hours - followed by a constant time-temperature drop from 160 degrees F. to 75 degrees F. over a period of 11 hours.

185 Degrees F. - a constant time-temperature rise from 75 degrees F. to 185 degrees F. over a period of 12 hours - followed by a constant time-temperature drop from 185 degrees F. to 75 degrees F. over a period of 10 hours.

Cycle III

135 Degrees F. - a constant time-temperature rise from 75 degrees F. to 115 degrees F. over a period of 1 hour - followed by a constant time-temperature rise from 115 degrees F. to 135 degrees F. over a period of $17\frac{1}{2}$ hours - followed by a constant time-temperature drop from 135 degrees F. to 75 degrees F. over a period of $3\frac{1}{2}$ hours.

160 Degrees F. - a constant time-temperature rise from 75 degrees F. to 140 degrees F. over a period of 1 hour, 10 minutes - followed by a constant time-temperature rise from 140 degrees F. to 160 degrees F. over a period of $15\frac{1}{2}$ hours - followed by a constant time-temperature drop from 160 degrees F. to 75 degrees F. over a period of 5 hours, 40 minutes.

185 Degrees F. - a constant time-temperature rise from 75 degrees F. to 165 degrees F. over a period of $1\frac{1}{2}$ hours - followed by a constant time-temperature rise from 165 degrees F. to 185 degrees F. over a period of 14 hours - followed by a constant time-temperature drop from 185 degrees F. to 75 degrees F. over a period of 7 hours.

Each cycle was operated at a condition of 100 percent relative humidity and atmospheric pressure.

Figures 11, 12 and 13, page 82, give the temperature versus time plots for each of the cycles and temperatures. The graphs were prepared from values obtained from the temperature record made for each curing treatment, with the "Brown" temperature recorder.

Hereafter in the tables, charts and discussions, the cycles will be referred to merely as Cycle I, Cycle II and Cycle III and their maximum temperatures.

Two mixes of 12 cylinders each were made for each of the cycles and the three maximum temperatures. This represented a total of 18 mixes or 216 cylinders tested. Of each mix 4 cylinders were used for control (i.e. subjected to moist curing only), 2 tested at 7 days and 2 tested at 28 days for compressive strengths.

The 8 remaining cylinders of each mix were steam cured and tested in the following manner: 2 tested at 29 hours (i.e. immediately after steam treatment); 2 stored in moist curing room for 6 days and then stored in laboratory air for 13 days and tested at 14 days; 2 stored in laboratory air for 13 days and tested at 14 days; 2 which were cured in sealed molds, stored in laboratory air for 13 days and tested at 14 days (these cylinders and results were used for the Heated Mold Investigation, Part III - Section II - Varying Temperature Heated Molds, as well as this investigation).

The concrete used was of one design mix of 0.5 water-cement ratio and each mix was altered as required by moisture condition of the materials to obtain a mix as close to the 0.5 water-cement ratio as possible.

Procedure

Handling and Preparation of Materials

The aggregates used in the mixes were stored in bins of 2 cubic yard capacity and fairly large changes in moisture contents were allowed. To overcome this the aggregates were brought out of the bins in 500 pound lots. Sufficient water was added to obtain a moisture content of 4 to 5 percent and aggregates were hand mixed thoroughly and placed in steel containers with tight fitting lids. Moisture content records of the aggregates were kept daily, and amount required for each mix taken from the containers immediately before mixing. In this way the moisture contents could be determined quite accurately and allowed good control of the concrete mix.

Batching

Each mix was made in the morning at approximately 9.00 to 10.00 a.m. Materials required for the mix were computed and weighed to the nearest ounce. The mixer used was the "Lancaster" described on page 32, and 4 minute mixing time was allowed. The method of charging the mixer was to add sand, gravel and cement and dry mix for 1 minute before adding the mixing water. A slump test was made using the standard A.S.T.M. slump cone immediately after completion of mixing time, and observations of rodability and workability of the mix were made at the same time.

Molding of Cylinders

The 4" x 8" steel cylinder molds described on page 36 were used - 10 of them were open topped and 2 were sealed. The concrete was molded in 3 layers, rodded 16 times each with a 3/8 diameter bullet-nosed rod.

Curing of Cylinders

After molding, the cylinders were left in the laboratory air for a presetting period of 5 hours. At the end of this time, the 4 control cylinders were removed to the moist room. The remaining 6 open top molds were removed from the cylinders, and the bare cylinders placed in the steam kiln along with the 2 sealed molds preparatory to steam curing. The steam kiln was then put into operation, as described on page 25, using the proper curing cycle. At the completion of the steam curing cycle, the cylinders were removed from the cabinet and given appropriate indentification numbers. The cylinders not tested immediately were stored in appropriate places until the time to be tested.

Testing of Cylinders

The test procedure was identical for each cylinder as follows:

> They were capped with sulphur and fire clay and tested in the Baldwin-Southwark Emery-Tate testing machine. The loading rate was 20,000 pounds per minute.

An auxiliary ball block was used between the loading plate and cylinder top to remove any eccentricity in loading. This was found necessary in order to obtain consistent strength values, since the diameter of the ball and socket of the regulator loading plate was too large to allow free movement under the ultimate load values of the cylinders.

Moisture content of one cylinder of each pair cured under identical conditions was taken immediately after the compression test.

Aggregate Tests and Materials

The aggregates used in this investigation were obtained locally from stock piles in general use in the Edmonton area.

Two coarse aggregates were used in the mix, namely Alberta Concrete Products 1" max, size gravel and Alberta Concrete Products ½" max. size gravel. The physical properties of these aggregates are given in Table VIII and the gradings of each are given in Tables IX and X.

The fine aggregate used was Elk Island pit-run sand. The physical properties of the sand are given in Table VIII and the grading is given in Table XI.

The cement used was Standard Exshaw Cement Type I as supplied by Gormans Limited, Edmonton, Alberta.

Ordinary domestic tap water was used for mixing the samples.

TABLE VIII

Physical Properties of Aggregates

Material	Physical Properties			
	Absorption (24 Hr) % by Weight	Bulk Sp. Gr.	Apparent Sp. Gr.	Specific Gravity Bulk Sat. & Surf. dry
1" agg.	1.0	2.60	2.65	2.62
½" agg.	1.3	2.61	2.70	2.65
Elk Island Sand	1.0	2.59	2.66	2.62

TABLE IX

Sieve Analysis of Coarse Aggregates

(Alberta Concrete Products 1" Agg.)

Sieve Size	Wt. Retained (lbs.)	% Retained	Cumulative % Retained
2"	0	0	0
1 1/2"	0	0	0
1"	3.81	9.1	9.1
3/4"	13.81	33.0	42.1
1/2"	16.87	40.4	82.5
3/8"	3.81	9.1	91.6
#4	3.12	7.5	99.1
Pan	0.37	0.9	100.0
Total	41.79	100.0	

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TABLE X

Sieve Analysis of Coarse Aggregates

(Alberta Concrete Products ½" Agg.)

Sieve Size	Wt. Retained (lbs.)	% Retained	Cumulative % Retained
1 "	0	0	0
1/2"	1.74	6.1	6.1
3/8"	5.35	18.8	24.9
#4	15.40	54.0	78.9
#8	1.68	5.9	84.8
#14	0.71	2.5	87.3
#28	0.57	2.0	89.3
#48	1.85	6.5	95.8
#100	0.56	2.1	97.9
Pan	0.56	2.1	100.0
Total	28.44	100.0	

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[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]

TABLE XI

Sieve Analysis of Fine Aggregates

(Elk Island Sand)

Sieve Size	Wt. Retained Gms.	% Retained	Cumulative % Retained	A.S.T.M. Standards
# 4	31.1	6.2	6.2	0-5
# 8	41.2	8.4	14. 6	
# 14	83.5	16.7	31.3	20-55
# 28	109.5	22.0	53.3	
# 48	202.5	40.5	93.8	70-90
#100	23.5	4.7	98.5	90-98
Pan	8.2	1.6	100.1	
Total	499.5	100.0	297.7	

Fineness Modulus 2.98

% Material Passing #200 Sieve = 1.1%

Organic Impurities - #2 color - (good for most concrete work)

Mix Designs

All mixes used in this investigation were designed for 0.50 water-cement ratio - (7 bags of cement per cubic yard) with a slump of 3".

Materials

Cement - Exshaw Standard Portland Cement Type I

Specific gravity 3.13

Sand - Elk Island

Specific gravity 2.62 - absorption 1.0%

Fineness modulus 2.98

Gravel - 1" max. size - Alberta Concrete Products

Specific gravity 2.62 - absorption 1.0%

½" max. size - Alberta Concrete Products

Specific gravity 2.65 - absorption 1.3%

Cement Content- 7 bags per cubic yard

Slump - 3 inch

Determination of Trial Mix Proportions

In order to obtain the best aggregate grading without re-sieving the 1" aggregate, ½" aggregate and sand were combined in proportions of 40%, 20% and 40% respectively.

water content - 305 pounds per cubic yard

cement content - $\frac{305}{0.5} = 610$ pounds per cubic yard

$= 6.97$ bags per cubic yard

absolute volume of water and cement -

$$\frac{305}{62.4} + \frac{610}{3.13 \times 62.4} = 4.89 + 3.14 = 8.03 \text{ cubic feet per cubic yard}$$

absolute volume of total aggregates - 27 - 8.03 = 18.97 cubic feet per cubic yard

absolute volume of sand - $0.40 \times 18.97 = 7.57$ cubic feet per cubic yard

absolute volume of 1" aggregate - $0.40 \times 18.97 = 7.60$ cubic feet per cubic yard

absolute volume of $\frac{1}{2}$" aggregate - $0.20 \times 18.97 = 3.80$ cubic feet per cubic yard

Sand content - $7.57 \times 2.62 \times 62.4 = 1236$ pounds

1" aggregate content - $7.57 \times 2.62 \times 62.4 = 1240.$pounds

$\frac{1}{2}$" aggregate content - $3.80 \times 2.65 \times 62.4 = 628$ pounds

Total Mix Proportions

305 pounds water; 610 pounds cement; 1236 pounds sand; 1240 pounds 1" aggregate; 628 pounds $\frac{1}{2}$" aggregate.

$$\frac{305}{610} : \frac{610}{610} : \frac{1236}{610} : \frac{1240}{610} : \frac{628}{610}$$

0.50 : 1 : 2.02 : 2.04 : 1.03

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Explanation of Tables and Figures

Figures 11, 12 and 13 are plots of temperature versus time for each of the three cycles, and the three maximum curing temperatures used. Also shown are corresponding cylinder temperatures for a sealed mold cylinder and a bare cylinder. The curves were plotted from data obtained from the "Brown" Temperature Recorder.

The concrete mix data and averages of 7 and 28 day moist cured control strengths are given in Table XII for each mix. The strengths listed are averages of two cylinders. Table XIII gives the detailed results for the individual control cylinders tested.

Figure 14 is the water-cement ratio versus average moist cured control strengths plot for each mix.

The strength results of Steam Curing for the three curing cycles and the four curing procedures are given in Tables XIV, XV, XVI and XVII. In all cases the strengths are expressed as a percentage of the corresponding average 7 and 28 day control strengths, as well as the average for each cycle and curing method.

Figures 15, 16, 17, 18 and 19 are obtained from values given in the above tables and are self-explanatory.

Figures 20 and 21 give compressive strengths versus time curves as compared to a standard moist cure, for each of the three cycles and the three tmperatures. The compressive strengths are shown as a percentage of the corresponding 28 day moist cured control strength. The standard compressive strength curve is obtained by averaging the 7 day moist cured strengths expressed as a percentage of the corresponding 28 day moist cured strengths.

Table XVIII lists the results of four mixes which for various reasons (as listed in the table) were not included in the previous tables and figures.

Figure 22 is a plot of the kiln temperature versus time for two mixes (included in Table XVIII) which were cured under extreme temperature variations resulting from inadvertant operation of the kiln.

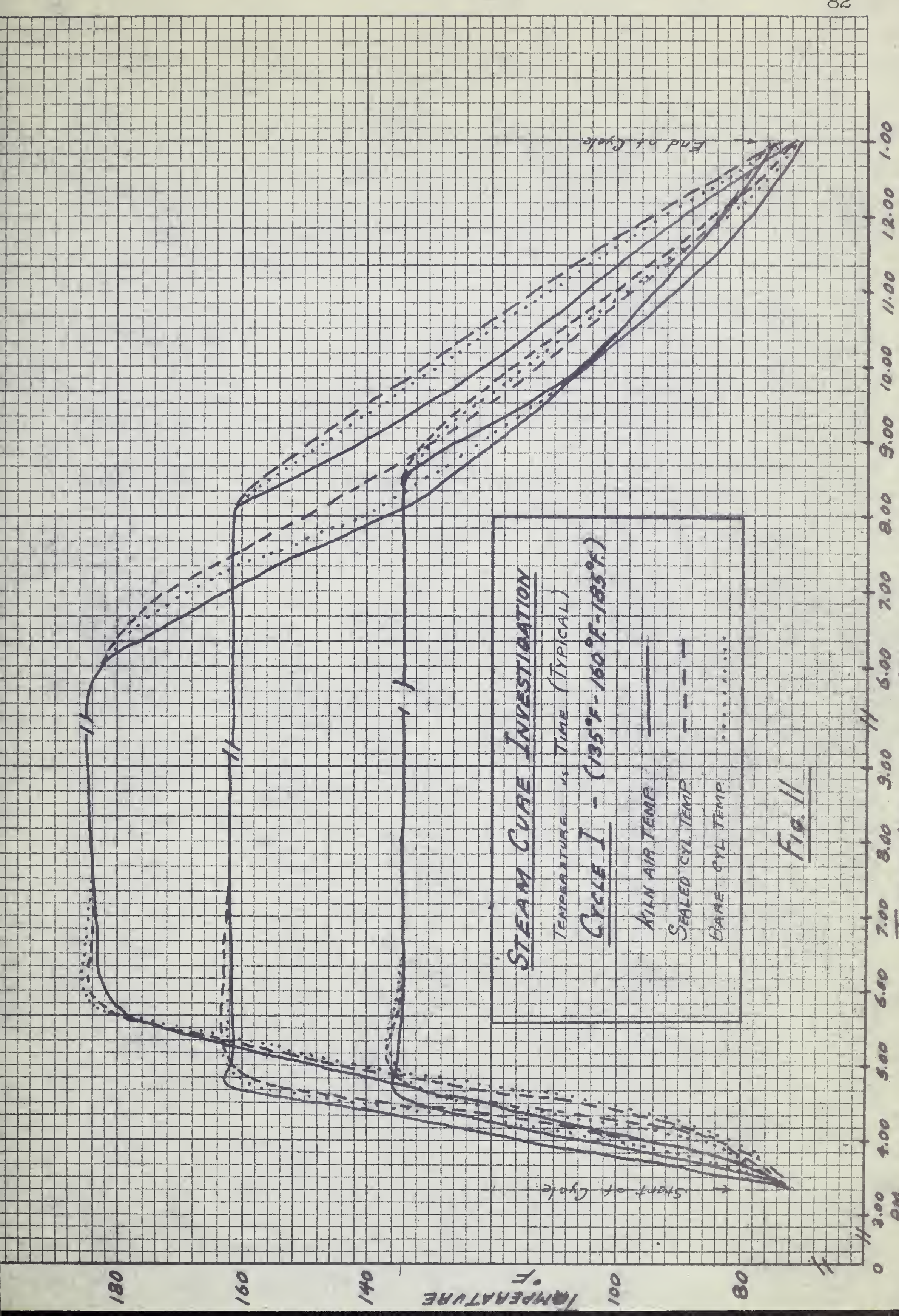
STEAM CURE INVESTIGATION
TEMPERATURE vs TIME (TYPICAL)
CYCLE I - (135°F - 160°F - 135°F)
KILN AIR TEMP
SEALED CYL TEMP
BARE CYL TEMP
Start of Cycle
End of Cycle
TEMPERATURE °F
80
100
140
160
180
TIME (hrs.)
0
2.00 P.M.
4.00
5.00
6.00
7.00
8.00
9.00
5.00
6.00 A.M.
7.00
8.00
9.00
10.00
11.00
12.00 P.M.
1.00

FIG. II

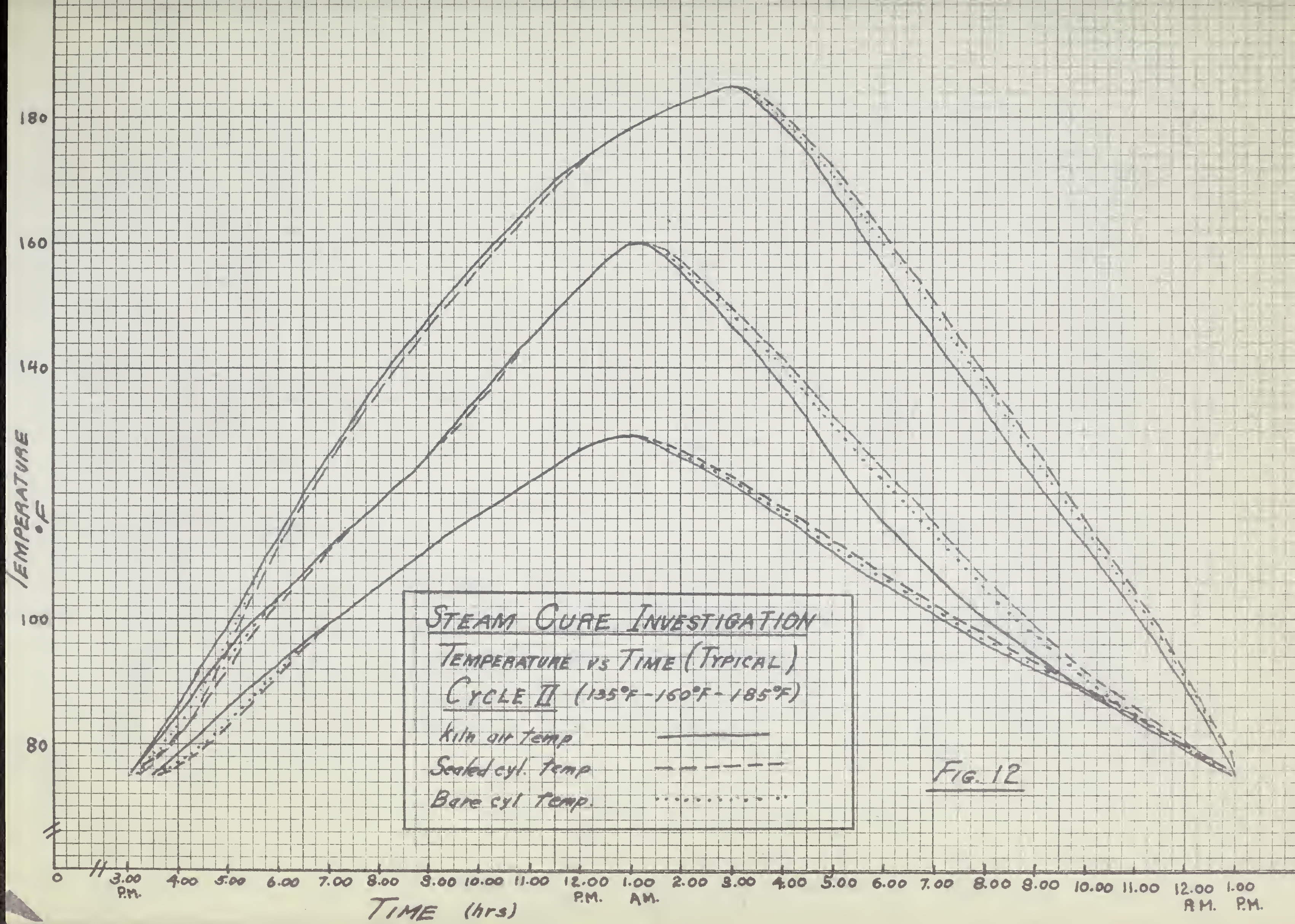
STEAM CURE INVESTIGATION
TEMPERATURE vs TIME (TYPICAL)
CYCLE II (135°F - 160°F - 185°F)
Kiln air temp
Sealed cyl. temp
Bare cyl temp.
TEMPERATURE °F
180
160
140
100
80
0
3.00 P.M.
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00 P.M.
1.00 A.M.
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00 A.M.
1.00 P.M.
TIME (hrs)

FIG. 12

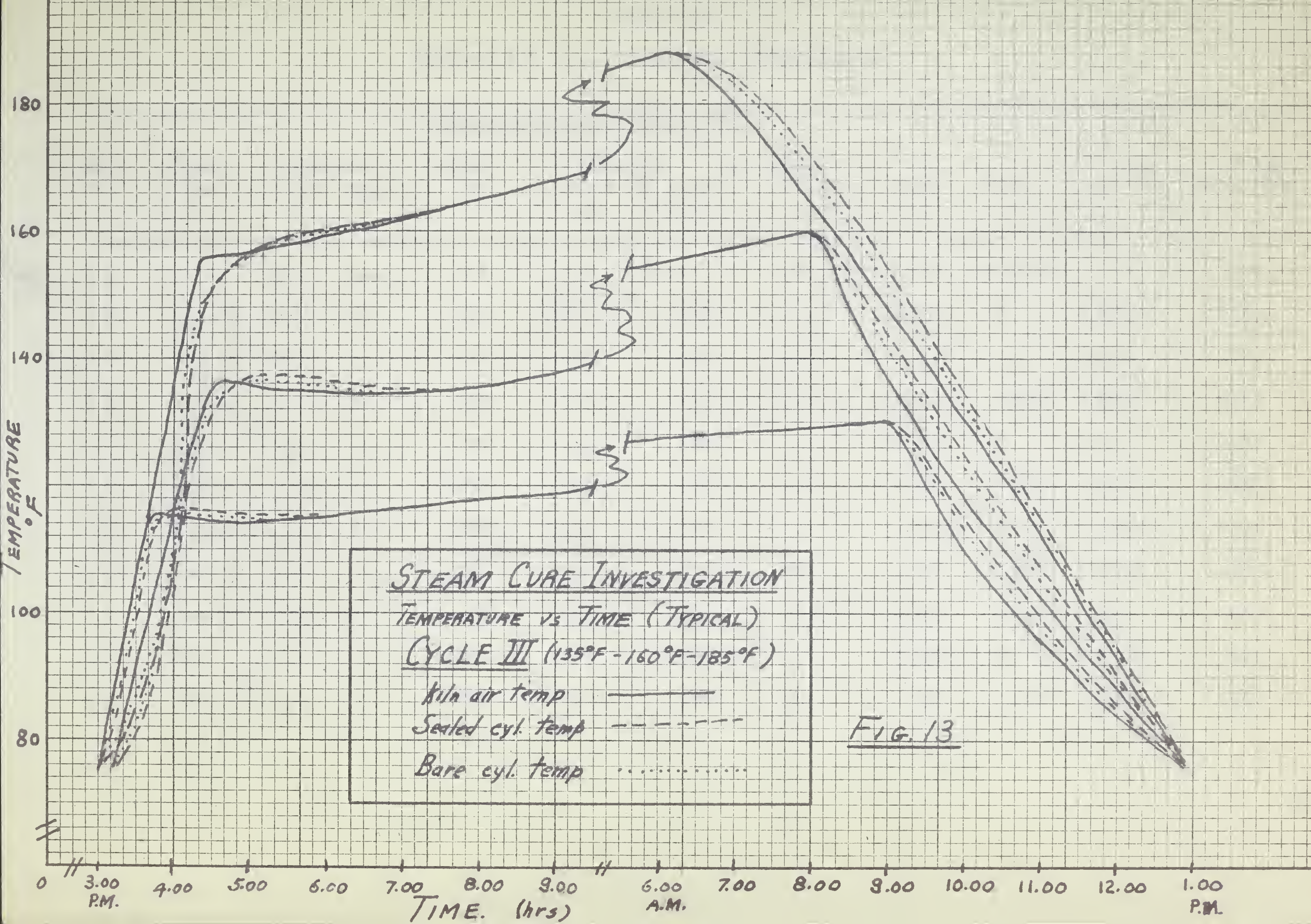
STEAM CURE INVESTIGATION
TEMPERATURE VS TIME (TYPICAL)
CYCLE III (135°F - 160°F - 185°F)
Kiln air temp
Sealed cyl. temp
Bare cyl. temp
TEMPERATURE °F
180
160
140
100
80
0
3.00 P.M.
4.00
5.00
6.00
7.00
8.00
9.00
6.00 A.M.
7.00
8.00
9.00
10.00
11.00
12.00
1.00 P.M.
TIME. (hrs)

FIG. 13

TABLE XII

CONCRETE MIX DATA - STEAM CURE INVESTIGATION

x - average of two cylinders

Mix No.	Date Cast	Cement lbs.	Cement bags	Sand lbs.	Gravel 1" size lbs.	Gravel ½" size lbs.	Water lbs.	W/C	Slump	x 7 Day Comp. Str.	x 28 Day Comp. Str.
		Mix Proportions per cubic yard									
1 D	Jan 15	584	6.66	1242	1237	642	308	0.528	3 1/2"	2195	3730
2 D	Jan 17	610	7	1230	1250	628	310	0.507	3"	2965	4355
3 D	Jan 18	610	7	1235	1255	630	313	0.512	3"	2785	4365
4 D	Jan 19	610	7	1230	1250	631	307	0.504	2 3/4"	3235	4785
5 D	Jan 22	610	7	1230	1248	630	312	0.510	3"	3015	4245
6 D	Jan 24	610	7	1234	1260	655	307	0.505	3 1/2"	2705	4085
7 D	Jan 25	610	7	1234	1248	624	311	0.510	3"	2625	4270
8 D	Jan 26	610	7	1235	1245	636	301	0.495	2 3/4"	3360	4855
9 D	Jan 29	610	7	1235	1245	628	306	0.500	3"	3380	4915
10D	Feb 1	610	7	1250	1245	625	303	0.498	3"	2750	4900
11D	Feb 2	610	7	1242	1250	627	302	0.495	2 1/2"	3165	4995

TABLE XII - Cont'd

CONCRETE MIX DATA - STEAM CURE INVESTIGATION

x - average of two cylinders

Mix No.	Date Cast	Cement lbs.	Cement bags	Sand lbs.	Gravel 1" size lbs.	Gravel ½" size lbs.	Water lbs.	W/C	Slump	x 7 Day Comp. Str.	x 28 Day Comp. Str.
		Mix Proportions per cubic yard									
12D	Feb 5	610	7	1235	1242	634	305	0.500	2 3/4"	3225	5210
13D	Feb 7	610	7	1240	1246	630	304	0.498	2 1/2"	3210	5200
14D	Feb 8	610	7	1240	1242	627	312	0.510	2 3/4"	3045	4900
15D	Feb 9	610	7	1240	1246	625	307	0.505	2"	3310	4635
16D	Feb 12	610	7	1234	1248	627	310	0.508	2 1/2"	3275	4730
17D	Feb 14	610	7	1235	1248	628	309	0.506	1 3/4"	3510	5275
18D	Feb 15	610	7	1240	1249	630	303	0.498	2"	3470	4885
19D	Feb 16	610	7	1236	1242	627	313	0.513	2 1/4"	3200	4550
20D	Feb 19	610	7	1235	1248	628	307	0.505	2 1/4"	3305	4710
21D	Feb 21	610	7	1234	1248	622	306	0.502	2 1/2"	3170	4780
22D	Feb 28	610	7	1234	1246	633	304	0.498	2 1/4"	3495	5200

TABLE XIII

STRENGTH RESULTS FOR MOIST CURE CONTROL - STEAM CURE INVESTIGATION

Mix No.	W/C	7 Day Comp. Str. (psi)	Moisture Content at Test	28 Day Comp. Str. (psi)	$(\text{Dev.})^2 \times 10^3$	Moisture Content at Test
1 D	0.528	2220	4.8	3700	1000.0	6.2
		2170	-	3760	885.0	-
2 D	0.507	2770	6.3	4390	96.1	14.8
		3160	-	4320	144.4	-
3 D	0.512	2790	6.3	4200	250.0	6.3
		2780	-	4530	289.0	-
4 D	0.504	3420	7.8	4740	1.6	6.5
		3050	-	4830	16.9	-
5 D	0.510	3110	6.4	4120	336.4	3.9
		2920	-	4370	108.9	-
6 D	0.505	2700	6.0	4060	409.6	8.1
		2710	-	4110	348.1	-
7 D	0.510	2560	5.5	4150	302.5	6.9
		2690	-	4390	96.1	-
8 D	0.495	3440	6.7	4960	67.6	7.3
		3300	-	4750	2.5	-
9 D	0.500	3300	6.0	4940	57.6	7.3
		3460	-	4890	36.1	-
10D	0.498	2740	7.1	5260	313.6	8.0
		2765	-	4540	25.6	-
11D	0.495	3180	7.6	5360	115.6	5.9
		3150	-	4630	4.9	-
12D	0.500	3220	6.3	5160	211.6	12.0
		3230	-	5260	313.6	-
13D	0.498	3190	6.9	5210	260.1	6.7
		3230	-	5180	230.4	-
14D	0.510	3070	7.7	4770	4.9	6.2
		3020	-	5030	108.9	-
15D	0.505	3280	4.8	4720	.4	5.3
		3340	-	4550	22.5	-
16D	0.508	3230	8.3	4730	.9	6.8
		3320	-	-	-	-
17D	0.506	3500	6.0	5020	102.4	6.5
		3520	-	5000	90.0	-
18D	0.498	3670	6.6	4740	1.6	5.3
		3260	-	5030	108.9	-
19D	0.513	3380	6.7	4550	22.5	6.0
		3320	-	-		-
20D	0.505	3370	7.5	4540	25.6	6.2
		3240	-	4875	30.6	-
21D	0.502	3145	8.2	4700	0.0	6.6
		3200	-	4860	25.6	-
22D	0.498	3440	5.2	5230	280.9	6.0
		3550	-	5170	220.9	-
				197,355	7040290.0	
			Average	4700	167,630.0	

Standard Deviation $\sqrt{167,630.0} = 410$

Coefficient of Variation $= \frac{410}{4700} = 0.087 = 8.7\%$

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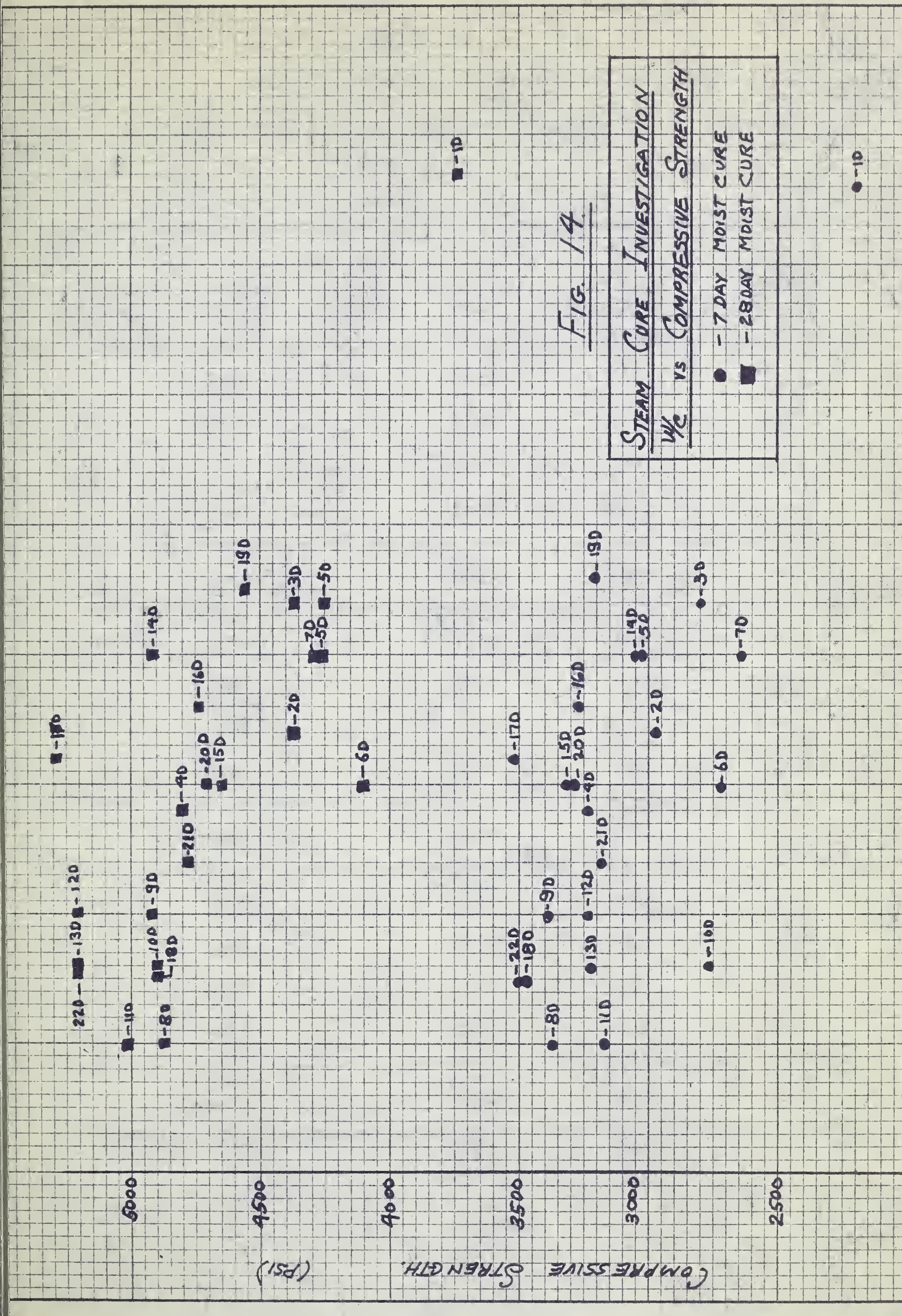

FIG. 14
STEAM CURE INVESTIGATION
W/C VS COMPRESSIVE STRENGTH

TABLE XIV

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD A - (24 hours steam - age at test - 24 hrs.)

CYCLE NO. I

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	22D5	5.10	2780	53.5	79.0
	22D6	-	2830	54.5	80.6
	3D5	6.85	2030	46.5	73.0
	3D6	-	2020	46.4	72.5
	Average		2415	50.2	76.3
160° F.	2D5	4.3	2820	64.6	95.0
	2D6	-	2460	56.4	82.8
	4D5	4.2	2185	45.6	74.2
	4D6	-	2660	55.6	89.7
	Average		2530	55.6	85.3
185° F.	5D5	5.45	2400	56.6	79.7
	5D6	-	2430	57.3	80.6
	6D5	4.3	1990	48.7	74.5
	6D6	-	2070	50.6	76.8
	Average		2225	53.3	77.9

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TABLE XIV - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD A - Cont'd

CYCLE NO. II

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	13D5	6.4	1935	37.2	60.4
	13D6	-	1900	36.6	59.2
	12D5	6.4	1980	38.0	61.4
	12D6	-	1915	36.7	59.5
	Average		1930	37.1	60.1
160° F.	9D5	4.6	2560	52.1	75.9
	9D6	-	2300	46.8	68.0
	21D5	3.8	2165	45.2	68.5
	21D6	-	2400	50.0	75.7
	Average		2355	48.5	72.0
185° F.	7D5	7.1	1900	44.5	72.4
	7D6	-	1890	44.4	72.0
	8D5	5.1	2130	43.8	63.3
	8D6	-	2240	46.2	66.7
	Average		2040	44.7	68.6

TABLE XIV - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD A - Cont'd

CYCLE NO. III

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	19D5	6.5	2210	48.6	69.1
	19D6	-	2290	50.5	71.6
	20D5	6.0	2570	54.5	77.6
	20D6	-	2620	55.5	79.2
	Average		2425	52.3	74.4
160° F.	17D5	5.2	2660	53.2	76.9
	17D6	-	2760	55.0	78.6
	18D5	5.8	2750	56.4	79.5
	18D6	-	2650	54.4	76.4
	Average		2705	54.8	77.8
185° F.	14D5	6.3	2490	50.8	81.8
	14D6	-	2510	51.2	82.4
	15D5	5.8	2830	61.0	86.5
	15D6	-	2845	61.5	86.5
	Average		2170	56.1	84.3

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TABLE XV

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD B - (24 hrs. steam, 4 days moist cure & 7 days lab. air)
(Age at test - 14 days)

CYCLE NO. I

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	22D7	4.6	4630	89.2	132.5
	22D8	-	4900	94.2	140.0
	3D7	7.4	3830	87.8	137.4
	3D8	-	3870	88.6	139.0
	Average		4560	89.9	137.2
160° F.	2D7	3.2	3530	81.0	119.0
	2D8	-	3500	80.0	118.0
	4D7	2.4	4280	89.6	132.5
	4D8	-	3870	81.0	119.8
	Average		3800	82.9	122.3
185° F.	5D7	2.3	3510	82.8	116.5
	5D8	-	3650	85.0	121.0
	6D7	2.7	2920	71.4	108.0
	6D8	-	3150	77.0	116.5
	Average		3310	79.0	115.2

TABLE XV - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD B - Cont'd

CYCLE NO. II

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F	12D7	3.9	4790	91.8	148.5
	12D8	-	4900	94.0	151.8
	13D7	4.0	4840	92.8	150.5
	13D8	-	4540	87.1	141.4
	Average		4770	91.4	148.0
160° F.	9D7	3.5	4750	95.8	140.5
	9D8	-	4810	98.0	142.4
	21D7	2.6	4700	98.4	148.0
	21D8	-	4580	95.8	144.5
	Average		4710	97.0	143.8
185° F.	7D7	2.8	3160	74.0	120.2
	7D8	-	3630	85.0	138.0
	8D7	3.3	3750	77.7	112.5
	8D8	-	3930	81.0	117.0
	Average		3625	79.4	121.9

TABLE XV - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD B - Cont'd

CYCLE NO. III

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	19D7	3.5	4590	96.4	143.0
	19D8	-	4400	96.4	137.5
	20D7	3.6	4520	95.8	136.5
	20D8	-	4550	96.6	137.0
	Average		4515	96.3	138.5
160° F.	17D7	3.4	4540	86.0	129.0
	17D8	-	4525	86.6	128.8
	18D7	3.2	4340	88.8	129.0
	18D8	-	4250	87.0	126.0
	Average		4415	87.1	128.2
185° F.	14D7	3.0	4040	81.2	132.4
	14D8	-	4200	85.8	138.0
	15D7	2.4	4250	91.8	128.4
	15D8	-	4450	96.0	134.4
	Average		4235	88.7	133.4

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TABLE XVI

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD C - (20 hrs. steam & 13 days lab. air)
(Age at test - 14 days)

CYCLE NO. I

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	22D9	1.9	4480	86.3	128.0
	22D10	-	4370	84.0	125.0
	3D9	2.9	3280	75.2	117.6
	3D10	-	3300	75.6	118.5
	Average		3855	80.3	122.3
160° F.	2D9	2.5	3570	81.8	120.3
	2D10	-	3480	80.0	117.3
	4D9	2.3	3900	81.5	120.4
	4D10	-	3640	79.8	112.8
	Average		3650	79.8	117.7
185° F.	5D9	1.9	3590	84.5	119.0
	5D10	-	3200	75.3	106.3
	6D9	2.0	2990	73.1	110.6
	6D10	-	2800	68.6	104.4
	Average		3120	75.4	110.1

TABLE XVI - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD C - Cont'd

CYCLE NO. II

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	12D9	5.4	4030	75.5	124.6
	12D10	-	3880	74.4	120.2
	13D9	3.0	4065	78.2	126.7
	13D10	-	4245	81.4	132.1
	Average		4055	77.6	125.9
160° F.	9D9	2.2	4190	85.3	124.0
	9D10	-	4200	85.4	124.4
	21D9	2.5	4250	89.0	134.0
	21D10	-	4100	85.7	129.0
	Average		4185	86.3	127.8
185° F.	7D9	2.1	3260	76.3	124.0
	7D10	-	3250	76.1	123.6
	8D9	2.6	3720	76.5	110.8
	8D10	-	3700	76.1	110.0
	Average		3480	76.3	117.1

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TABLE XVI - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD C - Cont'd

CYCLE NO. III

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	19D9	3.1	4040	88.8	126.5
	19D10	-	4030	88.5	126.0
	20D9	3.3	4500	95.5	133.0
	20D10	-	4400	93.3	136.0
	Average		4240	91.5	130.6
160° F.	17D9	2.9	4330	82.2	123.4
	17D10	-	4500	91.8	128.2
	18D9	2.4	4280	87.8	123.5
	18D10	-	4030	82.3	116.4
	Average		4285	86.0	122.9
185° F.	14D9	1.7	3830	78.2	125.6
	14D10	-	4080	83.2	134.0
	15D9	1.9	4050	87.5	122.3
	15D10	-	4170	90.0	126.8
	Average		4030	84.7	127.2

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TABLE XVII

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD D - (sealed molds - 24 hrs. steam & 13 days lab. air)
(age at test - 14 days)

CYCLE NO. I

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	22D11	-	4480	86.5	128.0
	22D12	-	4225	81.2	121.0
	3D11	3.0	3320	76.0	119.0
	3D12	-	3210	73.5	110.0
	Average		3810	79.3	119.5
160° F.	2D11	2.5	3770	86.5	127.0
	2D12	-	3730	85.5	125.8
	4D11	2.3	3650	76.2	113.0
	4D12	-	3370	70.5	104.0
	Average		3630	79.7	117.4
185° F.	5D11	2.3	3430	81.8	113.8
	5D12	-	3100	73.2	103.0
	6D11	1.9	3140	76.8	116.0
	6D12	-	2700	66.1	100.0
	Average		3090	74.5	108.2

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TABLE XVII - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD D - Cont'd

CYCLE NO. II

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	12D11	2.6	4100	78.6	127.1
	12D12	-	3870	74.3	120.0
	13D11	2.6	4160	80.0	133.5
	13D12	-	3820	73.4	131.0
	Average		3990	76.6	127.9
160° F.	9D11	2.4	4150	84.4	123.0
	9D12	-	4000	81.3	118.4
	21D11	3.8	4220	88.3	133.0
	21D12	-	4160	87.0	131.0
	Average		4130	85.2	126.3
185° F.	7D11	2.4	3330	78.0	126.8
	7D12	-	3100	72.6	118.0
	8D11	2.3	3620	74.5	107.8
	8D12	-	3600	74.2	107.0
	Average		3390	74.3	114.6

TABLE XVII - Cont'd

STRENGTH RESULTS - STEAM CURE INVESTIGATION

CURE METHOD D - Cont'd

CYCLE NO. III

Max. Temp.	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
135° F.	19D11	3.0	3900	85.8	107.0
	19D12	-	3920	86.2	144.6
	20D11	3.6	4160	88.4	126.0
	20D12	-	4140	88.0	125.6
	Average		4030	87.1	125.8
160° F.	17D11	2.5	4480	83.2	127.5
	17D12	-	4200	79.7	120.0
	18D11	2.3	4020	82.5	115.8
	18D12	-	4060	83.0	117.0
	Average		4190	82.1	120.1
185° F.	14D11	2.1	3610	73.7	118.3
	14D12	-	3720	75.8	122.0
	15D11	2.2	4290	92.6	129.3
	15D12	-	4430	96.0	134.0
	Average		4015	84.0	126.0

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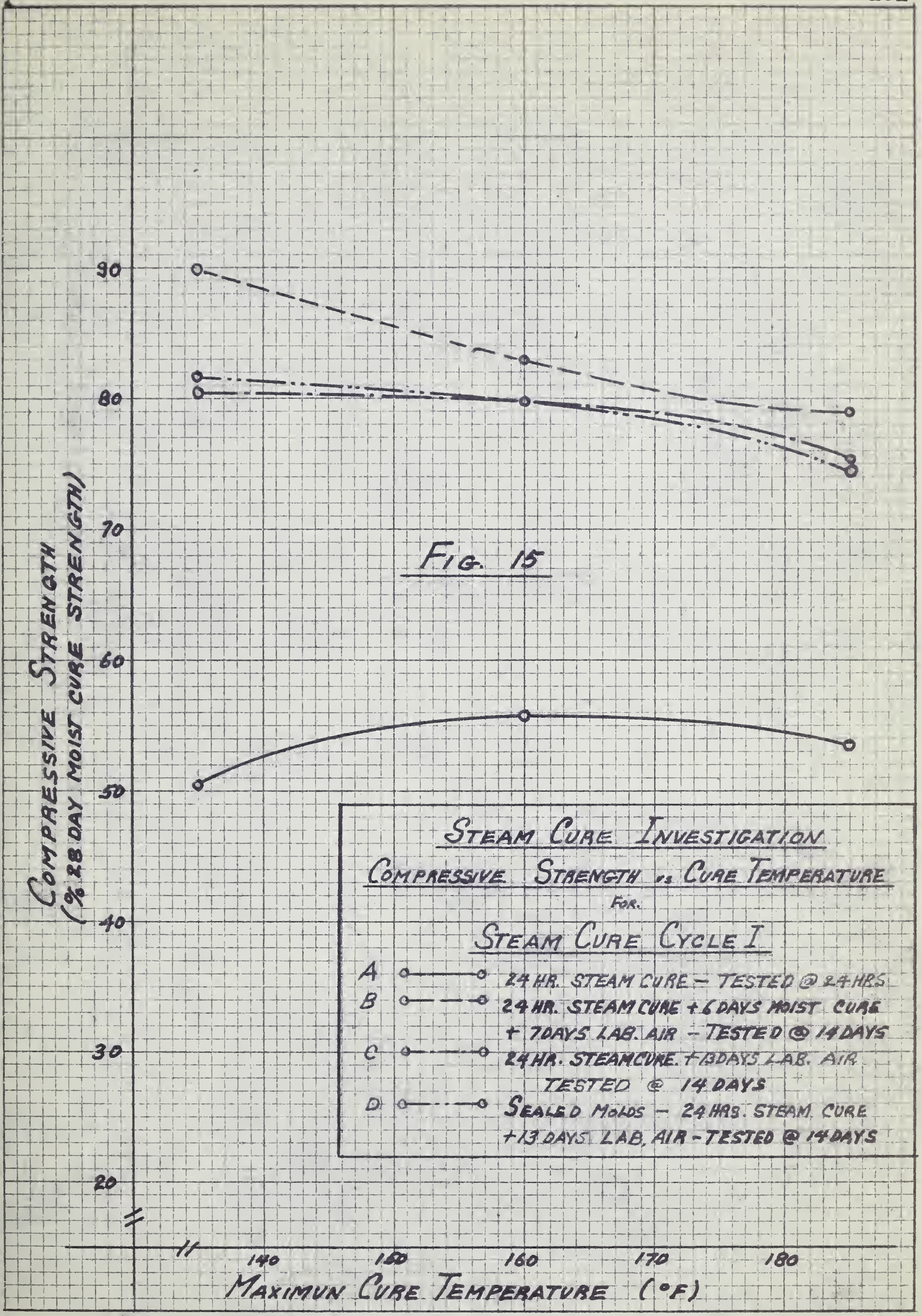
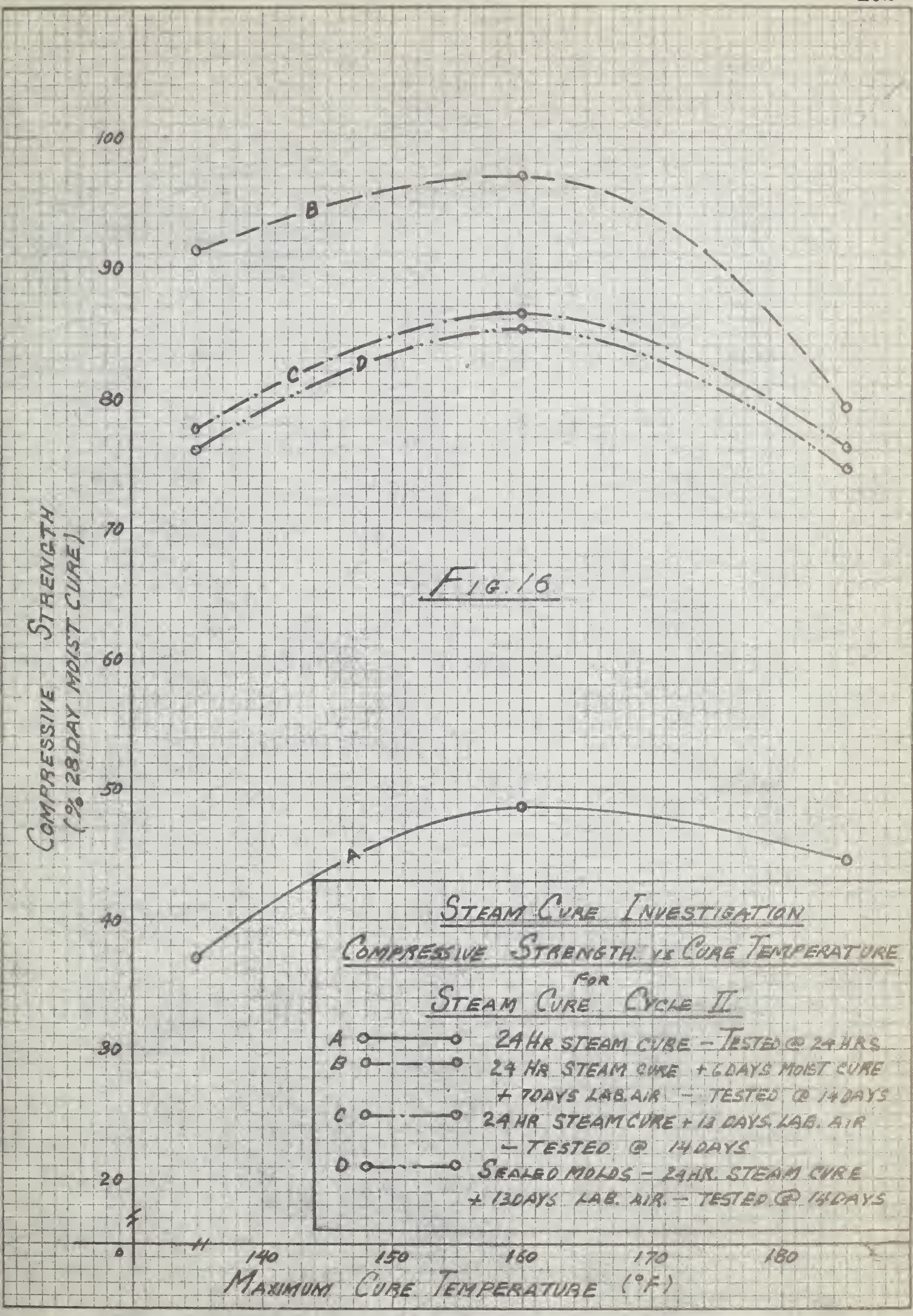


FIG. 15
STEAM CURE INVESTIGATION
COMPRESSIVE STRENGTH vs CURE TEMPERATURE
FOR
STEAM CURE CYCLE I
A 24 HR. STEAM CURE - TESTED @ 24 HRS
B 24 HR. STEAM CURE + 6 DAYS MOIST CURE + 7 DAYS LAB. AIR - TESTED @ 14 DAYS
C 24 HR. STEAMCURE + 13 DAYS LAB. AIR TESTED @ 14 DAYS
D SEALED MOLDS - 24 HRS. STEAM CURE +13 DAYS LAB. AIR - TESTED @ 14 DAYS
COMPRESSIVE STRENGTH (% 28 DAY MOIST CURE STRENGTH)
90
80
70
60
50
40
30
20
140
150
160
170
180
MAXIMUN CURE TEMPERATURE (°F)



COMPRESSIVE STRENGTH (% 28DAY MOIST CURE)
100
90
80
70
60
50
40
30
20
0
140
150
160
170
180
MAXIMUM CURE TEMPERATURE (°F)
A
B
C
D
FIG. 16
STEAM CURE INVESTIGATION
COMPRESSIVE STRENGTH VS CURE TEMPERATURE
FOR
STEAM CURE CYCLE II
A 24 HR STEAM CURE - TESTED @ 24 HRS
B 24 HR STEAM CURE + 6 DAYS MOIST CURE + 7 DAYS LAB. AIR - TESTED @ 14 DAYS
C 24 HR STEAM CURE + 13 DAYS LAB. AIR - TESTED @ 14 DAYS
D SEALED MOLDS - 24 HR. STEAM CURE + 13 DAYS LAB. AIR - TESTED @ 14 DAYS

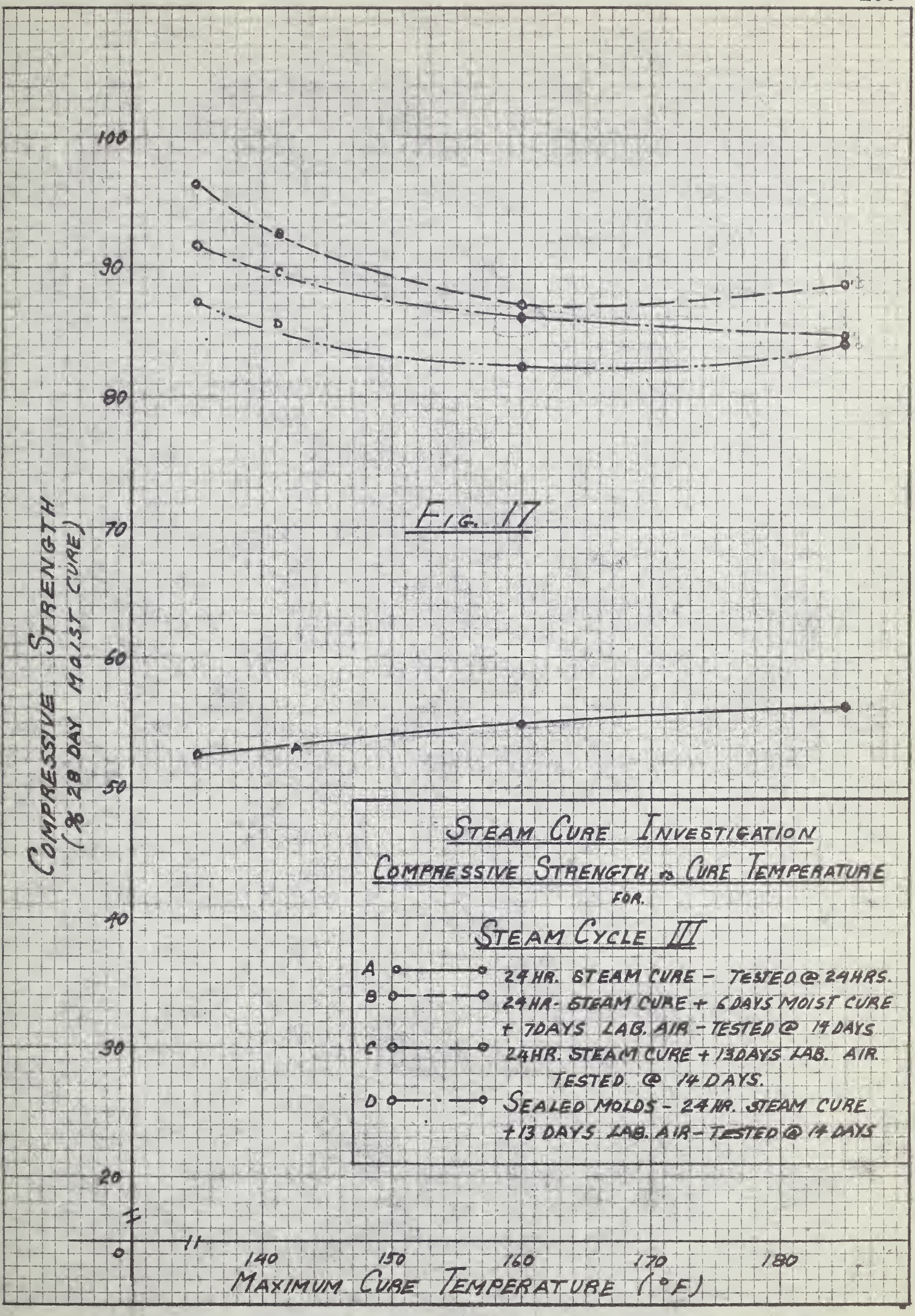


Fig. 17
Steam Cure Investigation
Compressive Strength vs Cure Temperature
for
Steam Cycle III
A 24 HR. STEAM CURE - TESTED @ 24 HRS.
B 24 HR. STEAM CURE + 6 DAYS MOIST CURE + 7 DAYS LAB. AIR - TESTED @ 14 DAYS
C 24 HR. STEAM CURE + 13 DAYS LAB. AIR. TESTED @ 14 DAYS.
D SEALED MOLDS - 24 HR. STEAM CURE +13 DAYS LAB. AIR - TESTED @ 14 DAYS
Compressive Strength (% 28 Day Moist Cure)
Maximum Cure Temperature (°F)
100
90
80
70
60
50
40
30
20
0
140
150
160
170
180

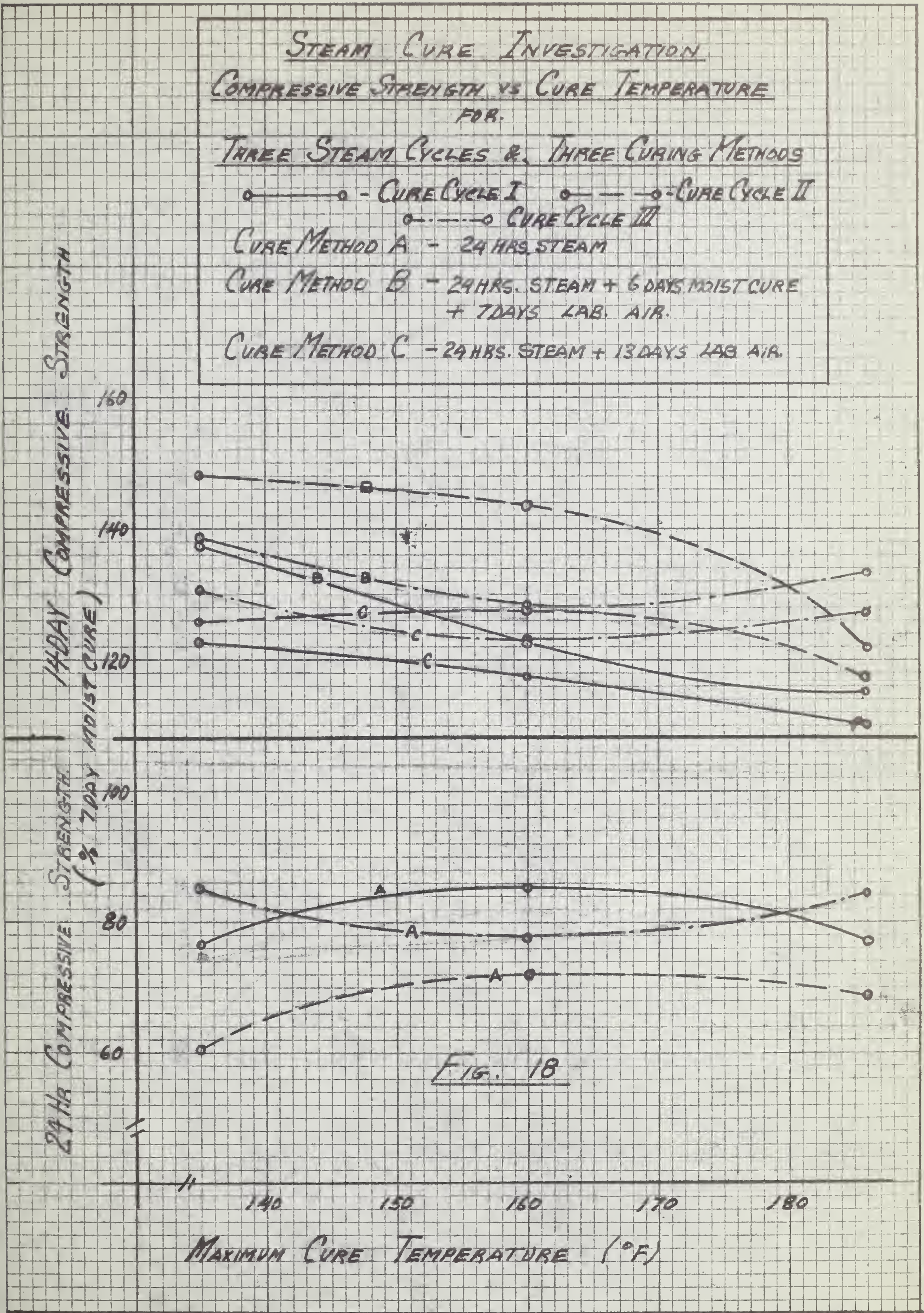

STEAM CURE INVESTIGATION
COMPRESSIVE STRENGTH vs CURE TEMPERATURE
FOR
THREE STEAM CYCLES & THREE CURING METHODS
- CURE CYCLE I
- CURE CYCLE II
CURE CYCLE III
CURE METHOD A - 24 HRS. STEAM
CURE METHOD B - 24 HRS. STEAM + 6 DAYS MOIST CURE + 7 DAYS LAB. AIR.
CURE METHOD C - 24 HRS. STEAM + 13 DAYS LAB AIR.
14 DAY COMPRESSIVE STRENGTH
24 HR COMPRESSIVE STRENGTH
(% 7 DAY MOIST CURE)
160
140
120
100
80
60
A
B
C
140
150
160
170
180
MAXIMUM CURE TEMPERATURE (°F)

FIG. 18

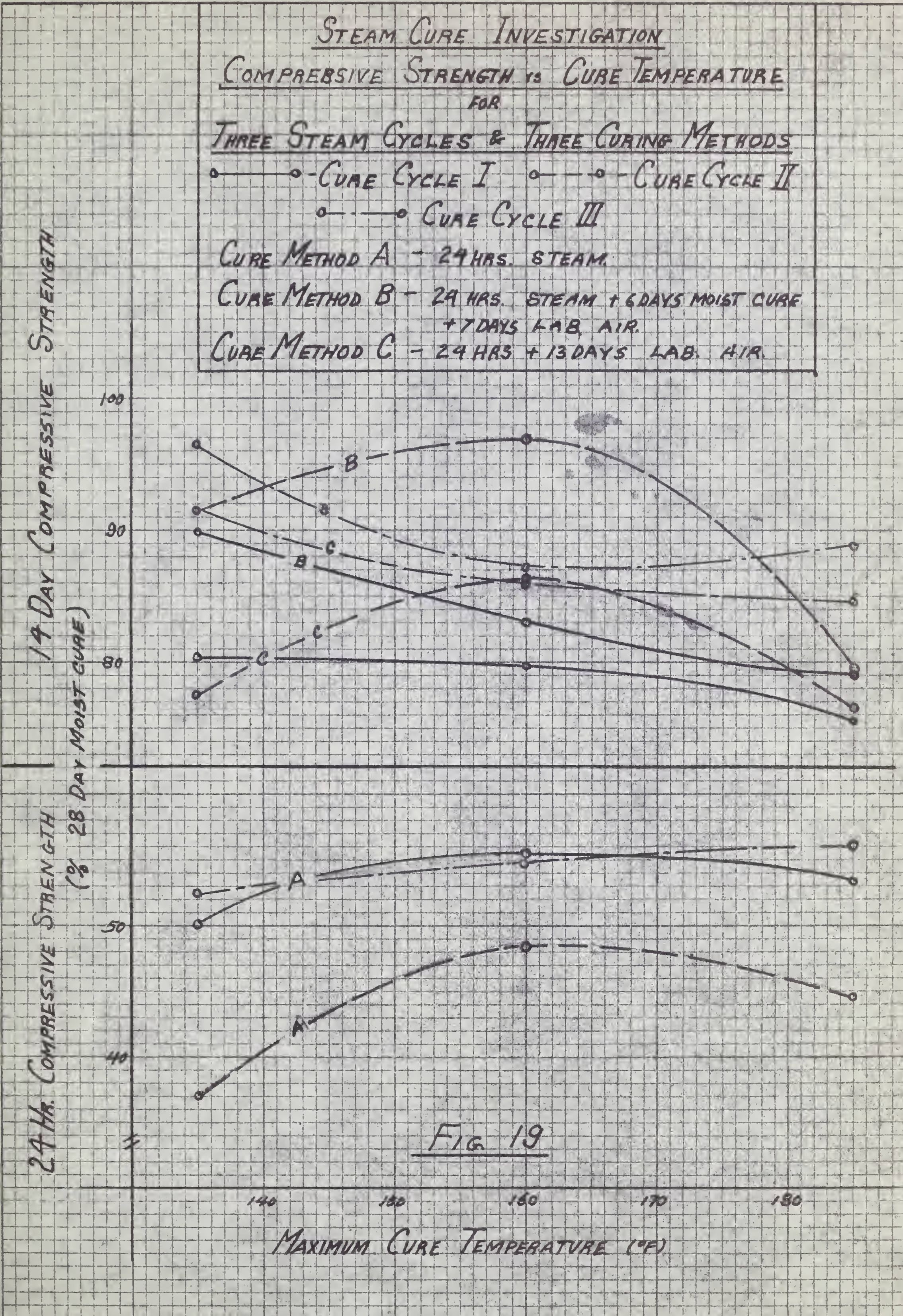

STEAM CURE INVESTIGATION
COMPRESSIVE STRENGTH vs CURE TEMPERATURE
FOR
THREE STEAM CYCLES & THREE CURING METHODS
CURE CYCLE I
CURE CYCLE II
CURE CYCLE III
CURE METHOD A - 24 HRS. STEAM
CURE METHOD B - 24 HRS. STEAM + 6 DAYS MOIST CURE + 7 DAYS LAB. AIR
CURE METHOD C - 24 HRS + 13 DAYS LAB. AIR
14 DAY COMPRESSIVE STRENGTH
24 HR. COMPRESSIVE STRENGTH
(% 28 DAY MOIST CURE)
100
90
80
50
40
A
B
C
140
150
160
170
180
MAXIMUM CURE TEMPERATURE (°F)

FIG. 19

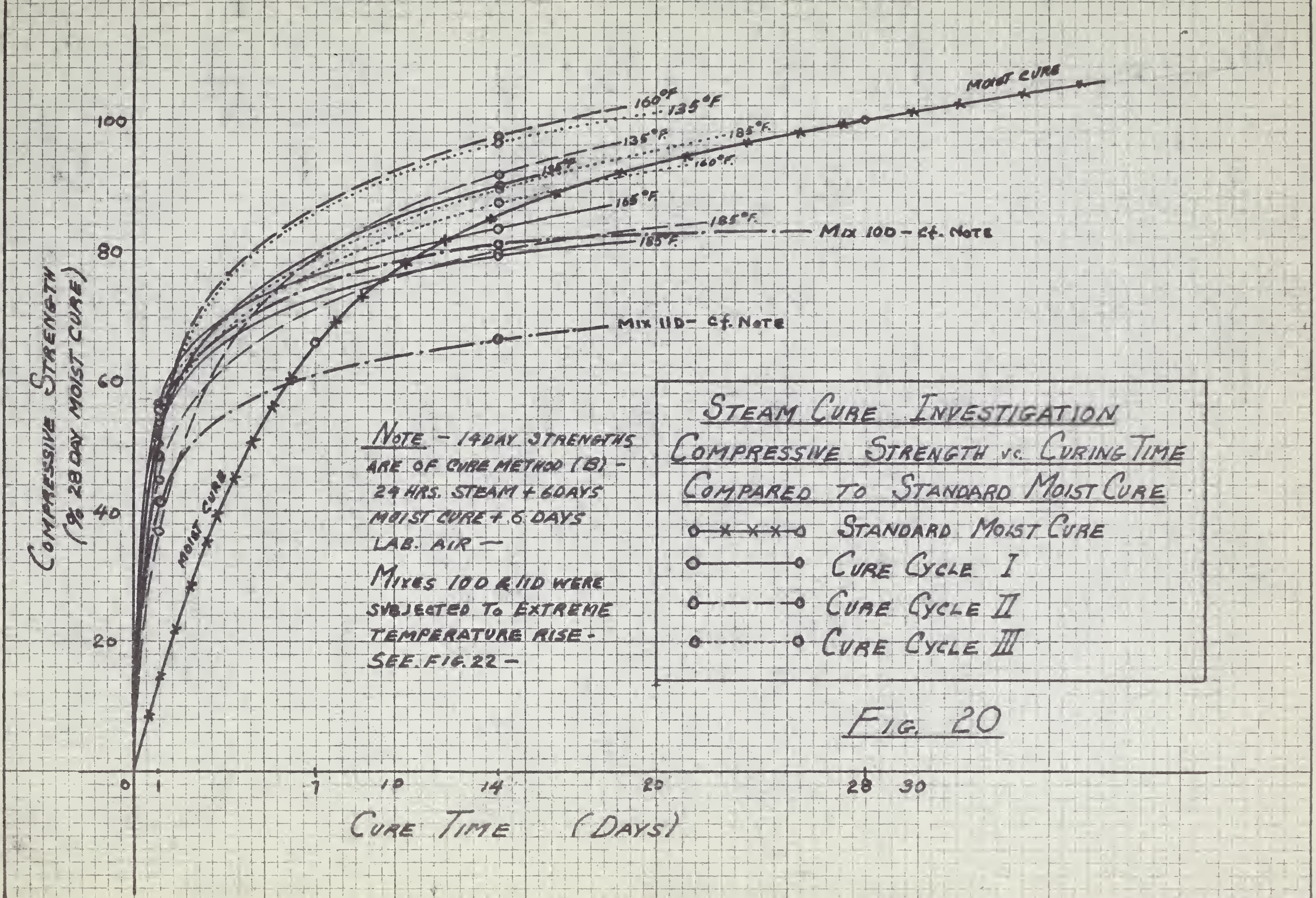
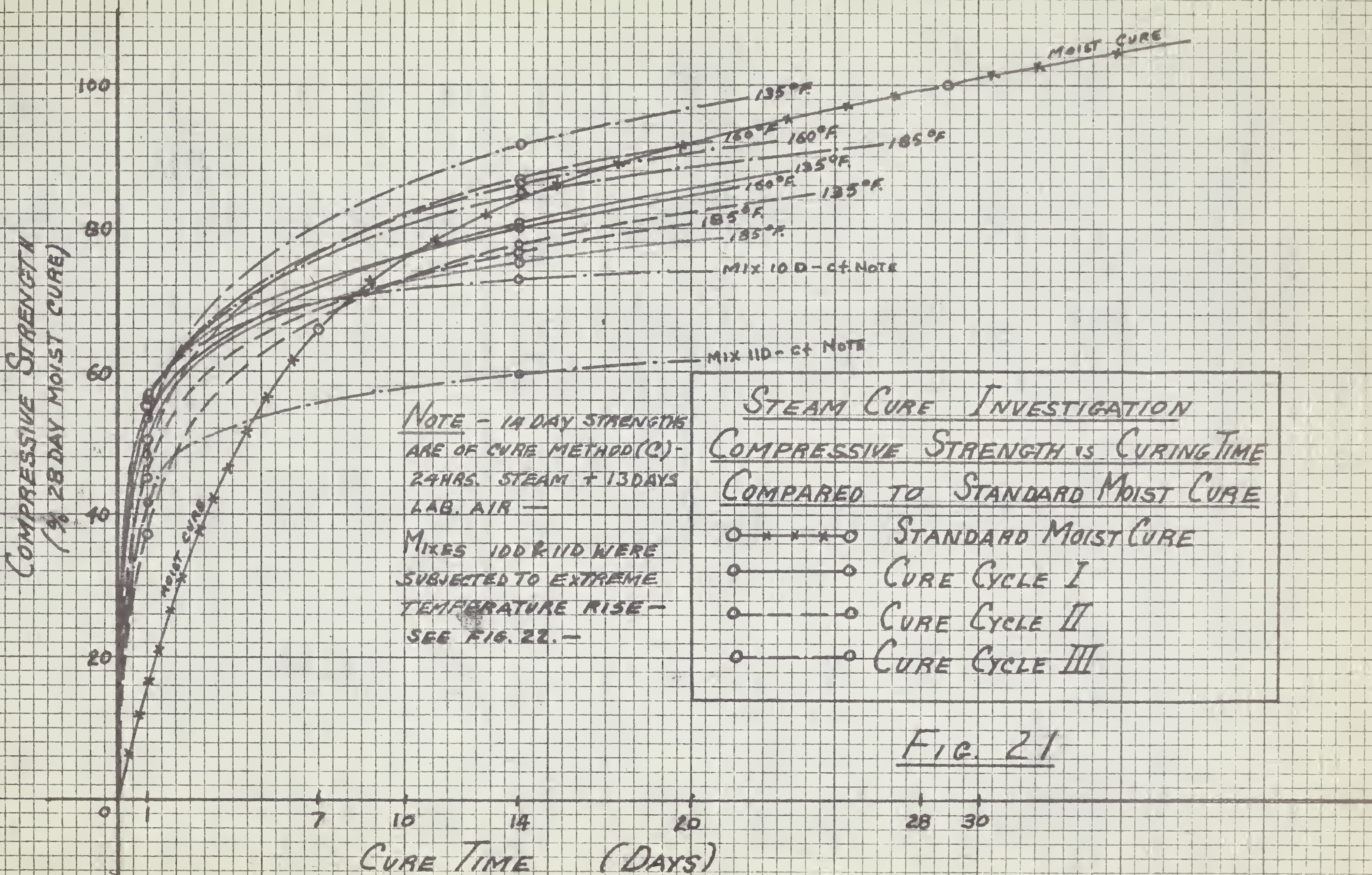

STEAM CURE INVESTIGATION
COMPRESSIVE STRENGTH vs. CURING TIME
COMPARED TO STANDARD MOIST CURE
STANDARD MOIST CURE
CURE CYCLE I
CURE CYCLE II
CURE CYCLE III
NOTE - 14 DAY STRENGTHS ARE OF CURE METHOD (B) - 24 HRS. STEAM + 6 DAYS MOIST CURE + 6 DAYS LAB. AIR -
MIXES 10D & 11D WERE SUBJECTED TO EXTREME TEMPERATURE RISE - SEE FIG. 22 -
MOIST CURE
MIX 10D - Cf. NOTE
MIX 11D - Cf. NOTE
160°F
135°F
185°F
COMPRESSIVE STRENGTH (% 28 DAY MOIST CURE)
CURE TIME (DAYS)
0
1
7
10
14
20
28
30
40
60
80
100

FIG. 20



Steam Cure Investigation
Compressive Strength vs Curing Time
Compared to Standard Moist Cure
Standard Moist Cure
Cure Cycle I
Cure Cycle II
Cure Cycle III
Note - 14 day strengths are of cure method (C) - 24 hrs. steam + 13 days lab. air —
Mixes 10D & 11D were subjected to extreme temperature rise — see Fig. 22. —
Moist Cure
135°F.
160°F
160°F
185°F
135°F.
160°F.
135°F.
185°F.
185°F.
Mix 10D - cf. Note
Mix 11D - cf Note
Moist Cure
Compressive Strength (% 28 day moist cure)
100
80
60
40
20
0
1
7
10
14
20
28
30
Cure Time (Days)

Fig. 21

TABLE XVIII

STRENGTH RESULTS - DISCARDED MIXES

MIX ID - Cured as Type I Cycle - 135° F. max. temp.
(Unsatisfactory w/c and cement content)

*

Cure	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
A	1D5	5.2	1580	42.4	72.2
	1D6	-	2280	61.1	104.0
B	1D7	1.6	3640	97.6	166.0
	1D8	-	3700	98.3	168.5
C	1D9	3.5	3370	90.6	153.0
	1D10	-	3060	82.0	139.0
D	1D11	2.5	3200	85.8	146.0
	1D12	-	3400	91.2	155.0

MIX 10D - Cycle II - 160° F. max. temp.
(Extreme temperature variations during cycle)
(see Figure 22 for temp. record)

Cure	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
A	10D5	3.7	2570	52.5	93.5
	10D6	-	2450	62.9	89.1
B	10D7	2.8	3900	79.6	142.0
	10D8	-	4000	81.6	145.0
C	10D9	2.1	3430	70.0	124.6
	10D10	-	3610	75.7	131.0
D	10D11	2.4	3180	65.0	115.6
	10D12	-	3610	75.7	131.0

TABLE XVIII - Cont'd

STRENGTH RESULTS - DISCARDED MIXES

Mix 11 D - Cycle II - 135° F. max. temp.
(Extreme temperature variations during cycle)
(see figure 22 for temp. record)

Cure	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
A	11D5	5.0	2120	42.5	67.0
	11D6	-	2060	41.2	65.2
B	11D7	2.3	3350	67.0	106.0
	11D8	-	3260	65.3	103.0
C	11D9	1.7	2860	57.2	90.5
	11D10	-	3080	61.7	97.4
D	11D11	2.3	3200	64.2	101.0
	11D12	-	3350	67.0	106.0

Mix 16D - Cycle III - 160° F. max. temp.
(Unknown water-cement ratio)

Cure	Specimen Number	Moisture Content at Test	Comp. Str. (psi)	% 28 Day Comp. Str.	% 7 Day Comp. Str.
A	16D5	5.5	2325	49.2	71.0
	16D6	-	2270	48.0	69.5
B	16D7	3.6	4070	86.0	124.3
	16D8	-	4320	91.3	132.0
C	16D9	2.4	3780	80.0	115.4
	16D10	-	3775	79.8	115.0
D	16D11	2.5	3610	76.4	110.0
	16D12	-	3315	70.0	101.0

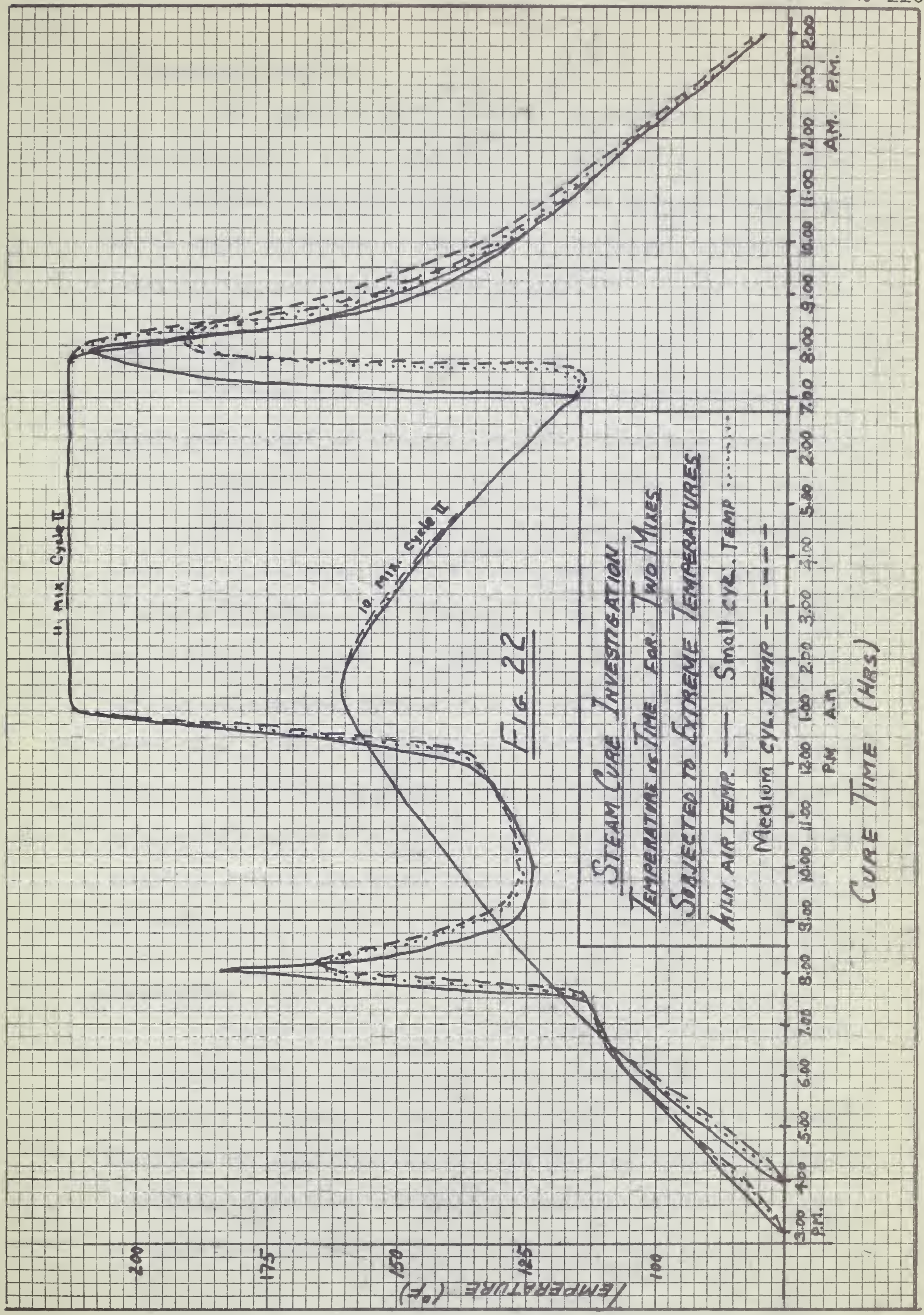


Fig 22
Steam Cure Investigation
Temperature vs Time for Two Mixes
Subjected to Extreme Temperatures
Kiln Air Temp ——
Small Cyl. Temp ....
Medium Cyl. Temp - - - - -
11 Mix Cycle II
10 Mix Cycle II
Temperature (°F)
200
175
150
125
100
Cure Time (Hrs)
3.00 P.M.
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00 P.M.
1.00 A.M.
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00 A.M.
1.00 P.M.
2.00

Discussions of Results

The strengths presented in all the tables and figures have been calculated as a percentage of the 7 and 28 day moist cured control strengths. This procedure was adopted in order to minimize variations due to difference in strengths of the control cylinders due to slight differences in water-cement ratios.

Control Strengths

A study of figure 14 and Tables XII and XIII shows that fairly good control was obtained for all the mixes used in the investigation, especially the correlation between 7 day and 28 day strength. That is, where 7 day strengths plotted low, on the water-cement ratio plot, the corresponding 28 day strengths were also low. This fact indicates the necessity of expressing all the results as percentages of the control strengths. An interesting condition is presented in that for all the mixes from 1D up to and including 10D, the points are in the lower portions of the groups. This is evidently due to the fact that a new job lot of cement was used for mixes from 10D to 22D and it gave slightly higher strengths when used in the same mix formula. This condition, however, is minimized when the results are presented as percentages of the control strengths.

Cure Cycles

Figures 15, 16 and 17 indicate that each of the cycles gave essentially similar results. The 24 hour strengths increased with temperature until temperatures in the vicinity of 160 - 170 degrees F. where reached, after which Cycles I and II showed a slight decrease for increasing temperatures, and Cycle III continued to give very slight increases in strengths.

In the case of the 14 day strengths, Cycle I gave highest strengths at 135 degrees F. and decreasing strengths with increasing temperature. Cycle II on the other hand produced the highest strengths at 160 degrees F., with 135 degrees F. producing strengths somewhat lower. The 185 degrees F. temperature in the case of Cycle II produced the lowest 14 day strengths. Cycle III was somewhat like Cycle I, in that 135 degrees F. produced the highest 14 day strengths, but the 160 degrees F. produced the highest 14 day strengths, but the 160 degrees F. temperature resulted in strengths slightly lower than those for 185 degrees F.

In all of the cycles the strenghts at 14 days for the two methods of cure (i.e. Cure Method B - 24 hours steam and 6 days moist air and 7 days laboratory air, and Cure Method C - 24 hours steam and 13 days laboratory air) the same relationship holds, in that the difference between the two methods is greatest at 135 degrees F. and that the difference decreases with an increase in temperatures. Cycle III beyond 160 degrees F. does not show this trend but it is probably due to inaccuracy of some of the points, particularly at 185 degrees F. for cure method B.

These results are in line with what would be expected, and the explanation is that at the lower curing temperatures the immediate 24 hour strengths are not fully developed, and this leaves a greater potential for strength to be gained when the specimens are cured for an additional 13 days. At higher temperatures the immediate 24 hour strength is increased, but the temperature obviously destroys some of the potential for strength gain in the subsequent

13 days storage. In the case of Cycles I and II the 185 degrees F. temperature appears to be high enough to reduce the immediate 24 hour strengths as well. In the case of Cycle III the gradually increasing temperature rise over the length of the cycle apparently reduces to some extent the effect of the elevated temperature.

The diminishing difference between Cure Methods B and C at 14 days can be explained by the same reasoning, i.e., the advantage of subsequent moist curing is reduced as the potential for strength gain is reduced with increasing temperatures.

An interesting and indicative feature is revealed in each of the three cycles in that the difference between Cure Methods C and D is in all cases very slight with the bare cylinders producing the higher strength values. (Cure Method D is identical to C except that for D the cylinders were enclosed in sealed molds during the steam curing treatment, so that the condition of the curing atmosphere could not affect the moisture in the concrete mix.) This indicates that a properly saturated atmosphere was created and maintained by the steam cabinet designed for this investigation.

Comparison of Curing Cycles I, II and III

A graphical comparison of the three cycles is given in figures 18 and 19 which show strengths obtained as a percentage of 7 and 28 day moist cured control strengths.

From the basis of immediate 24 hour strengths these figures indicate that Cycle I and Cycle III compare very closely, with Cycle I, giving slightly higher strengths at 160 degrees F. At 180 degrees F., however, Cycle III produces the higher 24 hour strength, the differences for both cycles being negligible. Cycle II produced 24 hour strengths considerably lower than the other cycles.

When considering strengths at 14 days, however, Cycle III developed strengths higher than Cycle I for all temperatures. Cycle II in this case produced strengths higher than the other cycles at 160 degrees F., especially in the case where there was 6 days moist curing following steam treatment. The strengths for 135 and 185 degrees F. were comparable to those of Cycle I.

The gradual temperature rise to a peak value, and followed by a gradual temperature drop in Cycle II, explains why the 24 hour strenghts of Cycle II are lower than those for Cycles I and III. The maximum temperature in the case of Cycle II is maintained for a considerably shorter period, and so would not develop the accelerated strengths to the same extent. At the same time it would not reduce the potential for strength gain to the same extent and consequently would account for the larger relative 14 day strengths, as well as the greater advantage of subsequent moist curing, which is especially noticeable at the 160 degrees F. temperature. The 185 degrees F. temperature apparently has an adverse effect, even when applied for short periods. The gradual temperature rise used in Cycle III similarly accounts for the slightly higher strengths than those for Cycle I.

Figures 20 and 21 also give a graphical comparison of the cycles and temperatures, and also give a comparison of strengths versus time, with the moist cured control cylinders. These curves show that early strengths increase with temperature, but that after steam curing further strength gain is not as rapid as for moist curing. The rate of strength gain decreases with temperature, and the long time strengths are less than the final strengths for moist cure, especially in the case of temperatures in excess of 160 degrees F.

The results from two mixes 10D and 11D which were subjected to rapid temperature rises to temperatures in excess of 200 degrees F. are also included in figures 20 and 21. These results forcibly indicate the adverse effects of thermal shock and higher temperatures during the curing cycle. As indicated in figure 22, mix 10D did not receive the rapid temperature rise until the cycle was almost completed, while 11D received two such treatments, one quite early in the cycle. The relative positions of the curves for these two mixes indicate that thermal shocks are not as disastrous when they occur near the end of the steaming cycle. The curves given in figures 20 and 21 agree in principle with similar relationships discussed in an article by Walter H. Price, entitled "Factors Influencing Concrete Strength" published in the February 1951 Journal of the American Concrete Institute (ACI proceedings Vol. 47).

The moisture content at test for one cylinder of each pair cured under identical conditions of each mix is also included in Tables of Strength Results. A comparison of the moisture contents and corresponding values expressed as a percentage, shows that where strengths were higher the moisture contents were lower. Due to the influence of other factors, such as variations in water-cement ratios, effects of steam curing and testing errors, it would be extremely difficult to draw any conclusions.

Summary of Conclusions

1. A properly saturated atmospheric pressure steam curing treatment will increase the early strengths of concrete. The strengths produced generally increase with temperature, up to temperatures in the vicinity of 160 - 170 degrees F., after which there is little, if any, further gain in strength.
2. After saturated atmospheric pressure steam curing treatment the rate of gain of strength is less than that of moist curing at 70 degrees F. and the long time strengths developed by steam cured cylinders are less than for moist curing at 70 degrees F.
3. The concrete specimens cured in saturated steam at atmospheric pressure gain strength more rapidly when subjected to a period of moist curing, than when subjected to yard storage, but the advantage decreases with an increase in curing temperature used.
4. The strengths developed by saturated atmospheric pressure curing are affected to some extent by the type of curing cycle used.
5. Thermal shock and high temperatures during steam curing have an adverse effect on both early and long time strengths.

PART V

Application of Results to Practice

The results of this investigation indicate that a very considerable increase in early strengths is obtainable from a properly executed saturated atmospheric steam curing program. Such early strengths would reduce yard storage necessary, and enable a producer to place his concrete products on the market more quickly.

The results also indicate that curing temperatures in excess of 165 - 170 degrees F. do not appear to be economically feasible, since the slight increase in early strengths obtainable would be offset by the increased cost of maintaining higher temperatures, as well as by the increased cost of concrete mixes of sufficiently increased strengths so as to meet 28 day strength specifications.

Also considerable care must be used in designing curing kilns, and operating them so that thermal shock, and improper curing conditions will not adversely affect the concrete products.

Suggested Further Investigations

This investigation has covered a very minor portion of the field of steam curing as a method of obtaining accelerated strength in concrete manufacture. However it does constitute a beginning, from which many questions arise.

A few suggestions for further investigation concerning the effect of atmospheric steam curing of Portland Cement concrete are listed below:

1. More information is required along the lines of this investigation, particularly with respect to other temperatures

between 75 degrees and 200 degrees F. and the long time strengths resulting from subsequent storage.

2. The effect on flexural strengths, modulus of rupture and durability of normal concrete mixes as well as air entrained mixes, is not definitely known and further data is required.

3. The effect of steam curing on the properties of concrete with widely varying water-cement ratios, water content per cubic yard and aggregate gradings and aggregate types is yet to be investigated.

4. Reliable data on the effect of curing conditions maintained at various percentages of saturation and composition is required to determine the lower limits of moisture and temperature requirements for good curing conditions.

5. Additional data on the effect of steam curing on concrete mixes using the different types of Portland Cement is required to indicate possible need of variation in techniques to obtain optimum results.

At the present time very little information is available with regard to these problems and only through a proper investigation will reliable answers be forthcoming.

Under the present conditions of increasing construction trends and increasing shortages of construction materials, more and more impetus is placed on the use of concrete products to take the place of other building materials, as well as increased production

for normal uses of concrete. In order to meet this demand, increasingly efficient methods must be adopted in producing concrete, while still maintaining high standards of quality. The information obtained from investigations are of inifinite value in this respect and will ensure that concrete will continue to be used even when the other construction materials become easily available again.

BIBLIOGRAPHY

"High Pressure Steam Curing" - a progress report by A.C.I., Committee 716, April 1944, Vol 40, pp 409-16.

"Studies of High Pressure Steam Curing" - by J.C. Pearson and E.M. Brickett, Proceedings A.C.I., 1932, Vol 28, pp 537.

"The Effect of High Pressure Steam on Crushing Strength of Portland Cement Mortars and Concretes" by R.J. Wig, A.S.T.M., Vol. 11, 1911, pp 580.

"Strength and Resistance to Sulphate Waters of Concrete Cured in Water Vapour at Temperatures between 100 and 350 degrees F." - D.G. Miller, Proceeding A.S.T.M. 1930, Vol. 30, Part II - Technical papers, pp 636.

"Effect of Steam Treatment of Portland Cement Mortars on their Resistance to Sulphate Action" - by T. Thorvaldson and V.A. Vigfusson. Engineering Journal, March 1928, pp 174.

"Concrete Masonry" - by Amund M. Korsmo, H.H.FA. Technical Bulletin, No. 9, March 1949, pp 7.

"Early Strength of Concrete as Affected by Steam Curing Temperatures" - by Joseph J. Shideler and Wilbur H. Chamberlain, A.C.I. Journal, December 1949, proc. Vol. 46, pp 273.

"Steam Curing of Concrete" - by R.W. Nurse, "Magazine of Concrete Research", June 1949, No. 2, pp 79 (British Publication).

"Curing - Most Efficient Methods Determined by Tests" - by George A. Mansfield, "Rock Products" Journal, February 1947.

"Curing - A Problem in Thermodynamics" - by George A. Mansfield, "Rock Products" Journal, August 1948.

"High Temperature, High Humidity" - by Bror Nordberg, "Rock Products" Journal, January 1947.

"Factors Influencing Concrete Strengths" - by Walter H. Price, A.C.I. Journal, February 1951, Proc. Vol. 47 pp .

"Concrete Manual" by United States Department of Interior - Bureau of Reclamation, Denver, Colorado.

"Heating, Ventilating and Air Conditioning Guide, 1946" - by American Society of Heating and Ventilating Engineers.

"Humid Air and Super-heated Steam as a Drying Media for Rigid Porous Solids" - Progress Report No. 2, Project M715, Owens-Illinois Glass Co., by G.W. Govier, August 30, 1947.